Evidence for MOND-type modified gravity in galactic rotation curves and wide binary stars

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Collaborators and those who helped

- Galactic rotation curves: the SPARC team (McGaugh, Lelli, Schombert, Li) and Harry Desmond
- Wide binaries: Kareem El-Badry (most inputs were discussed with him). I was driven to this independent work on wide binaries following discussions with Indranil Banik and Will Sutherland. See also Thursday morning session.

Bekenstein & Milgrom's question in the 1984 ApJ paper proposing "AQUAL", a modified Poisson equation for the non-relativistic gravitational potential:

Does the missing mass problem signal the breakdown of Newtonian gravity?

Can **current astronomical data** offer a definite or **smoking-gun evidence**?

Two sets of independent data taken together say clearly yes!

- galactic rotation curves from the **SPARC** database (Lelli, McGaugh, & Schombert 2016)

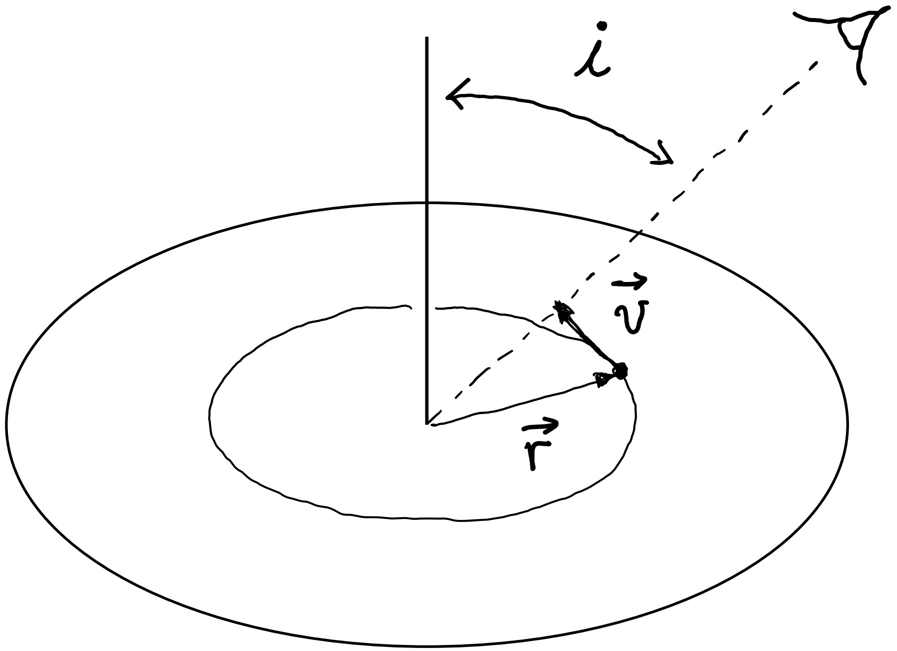
- wide binary stars from **Gaia DR3** (https://www.cosmos.esa.int/web/gaia/data-release-3)

Here I give a brief description of recent explorations.

- Kyu-Hyun Chae, Federico Lelli, Harry Desmond, Stacy S. McGaugh, Pengfei Li, and James M. Schombert, 2020, *ApJ* **904** 51
- Kyu-Hyun Chae, Federico Lelli, Harry Desmond, Stacy S. McGaugh, and James M. Schombert, 2021, *ApJ* **921** 104
- Kyu-Hyun Chae, Federico Lelli, Harry Desmond, Stacy S. McGaugh, and James M. Schombert 2022, Phys. Rev. D 106, 103025
- Kyu-Hyun Chae, 2022, *ApJ* **941** 55
- Kyu-Hyun Chae, 2023, arXiv:2305.04613 (submitted to ApJ, a revised version will appear on arXiv soon)

Orbits of gas particles or stars:

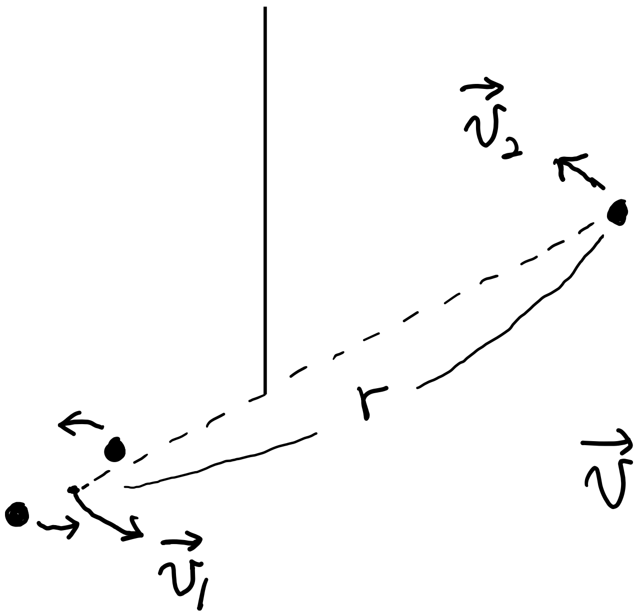
galactic disks



$$g_N = \left| \frac{\partial \Phi_N}{\partial r} \right| , \quad g = \frac{v^2}{r}$$

(Newtonian) (kinematic)

binary stars



$$\vec{v} = \vec{v}_2 - \vec{v}_1$$

$$g_N = \frac{G M_{tot}}{r^2} , \quad g = \frac{v^2}{r}$$

Orbital motions in galactic disks

- Pros

- Well measured inclinations + low eccentricities: measured radial velocities (v_r) can be reliably transformed to orbital velocities (v).
- Stellar light and hydrogen gas distributions can be well measured: Newtonian orbital velocities can be calculated in a straightforward way.
- Radial acceleration data (g_{N}, g) are well defined and can be easily compared with predictions of gravity theories.

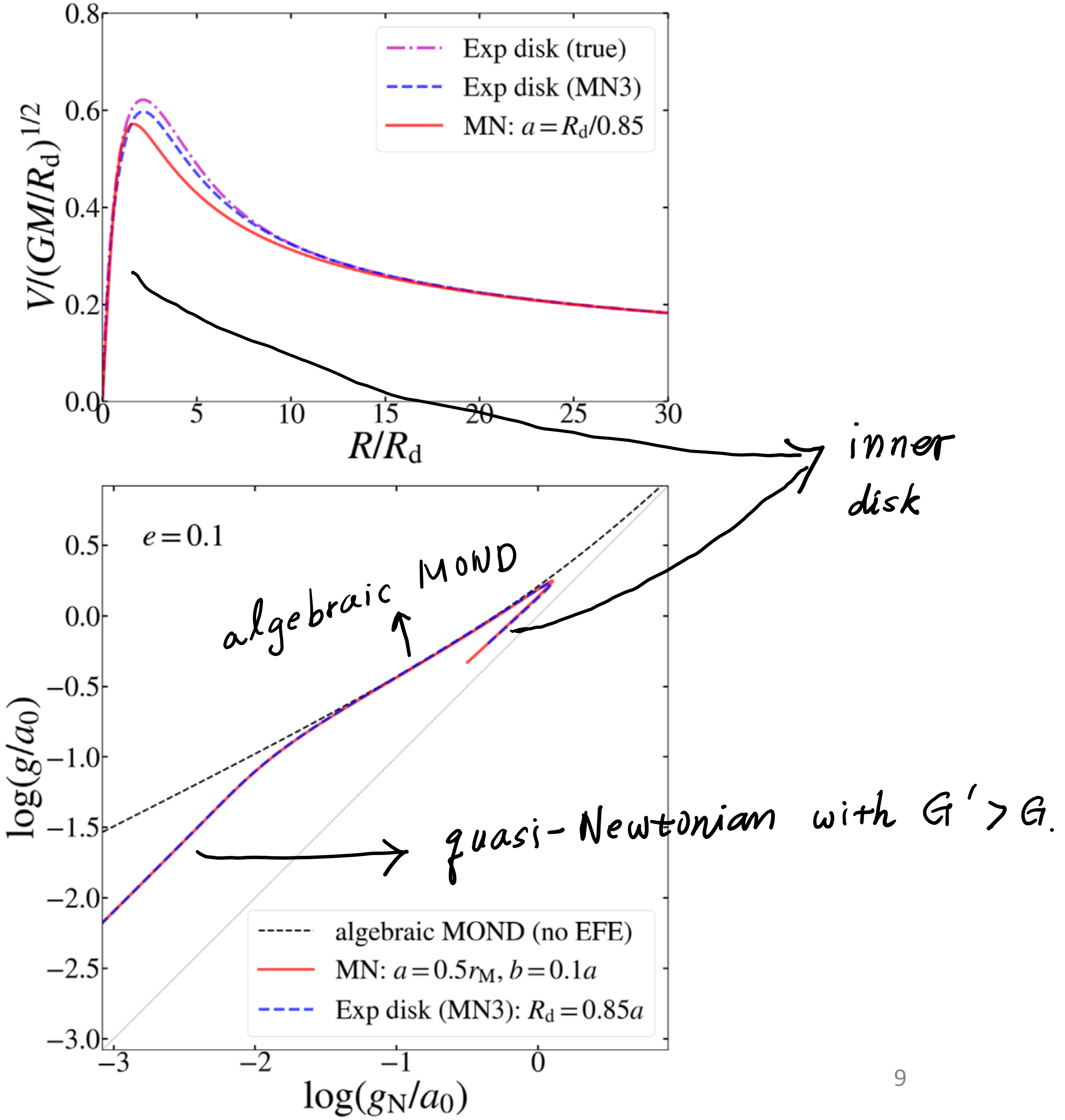
- Cons

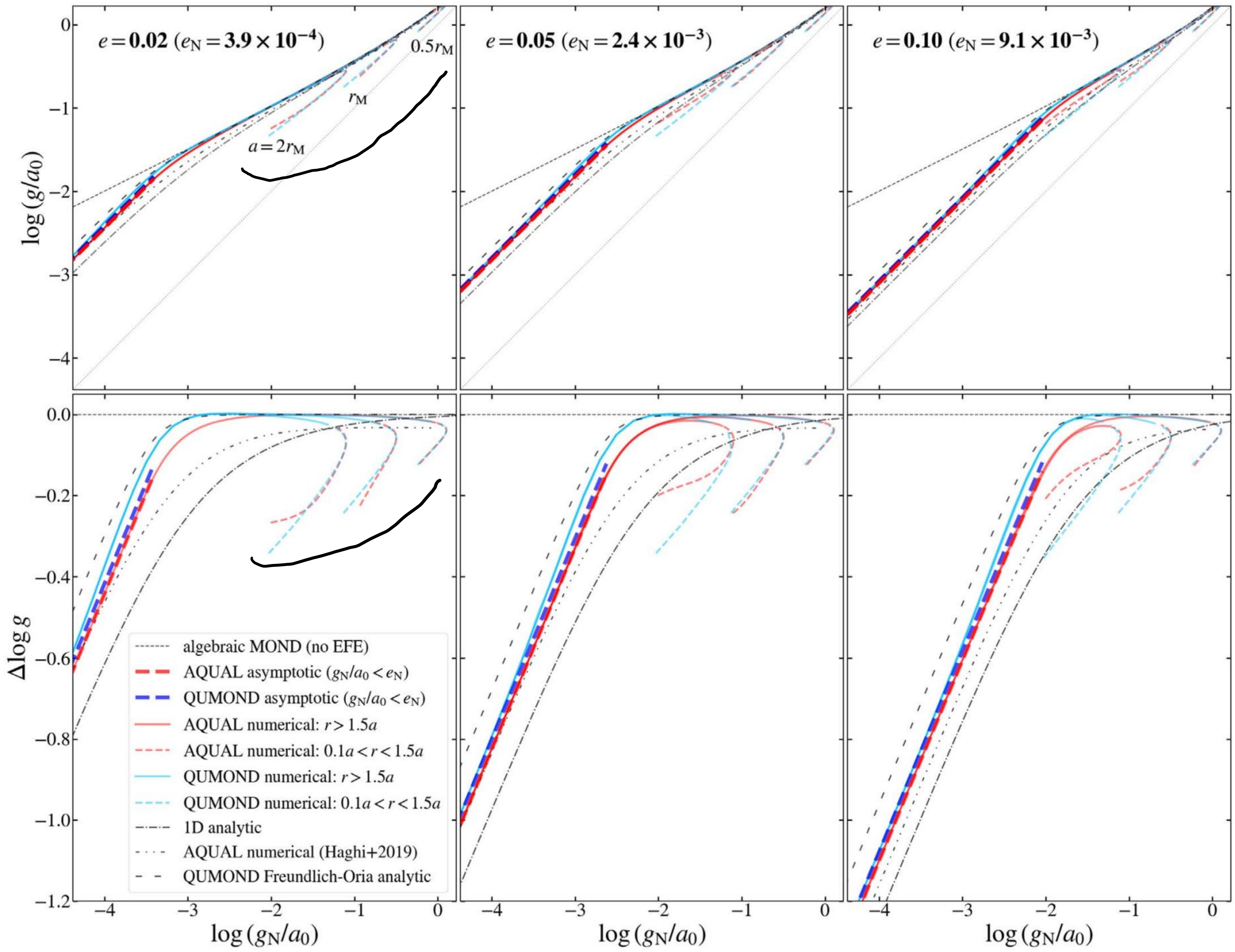
- Uncertainties in radial velocities
- Uncertainties in mass-to-light ratios of the disk (and the bulge)
- Uncertainties in total gas-to-hydrogen mass ratio
- Must deal with degenerate predictions of dark matter (w/ standard gravity) and modified gravity.

Orbital motions in wide binaries

- Pros
- Proper motions and distances are accurately measured: sky-projected (transverse) relative velocities (v_p) and separations (s) are accurately measured.
- Absolute magnitudes (luminosities) are accurately measured: stellar masses can be well determined through a mass-magnitude relation.
- Dark matter cannot play any role: standard and modified gravities can be compared regardless of the presence or absence of dark matter.
- Cons
- **Inclinations** are unknown: **projections effects** need to be properly taken into account.
- **Eccentricities** are poorly determined: large uncertainties in transforming v_p to the magnitude of the 3D relative velocity v.
- **Hidden/undetected additional components** need to be properly taken into account.

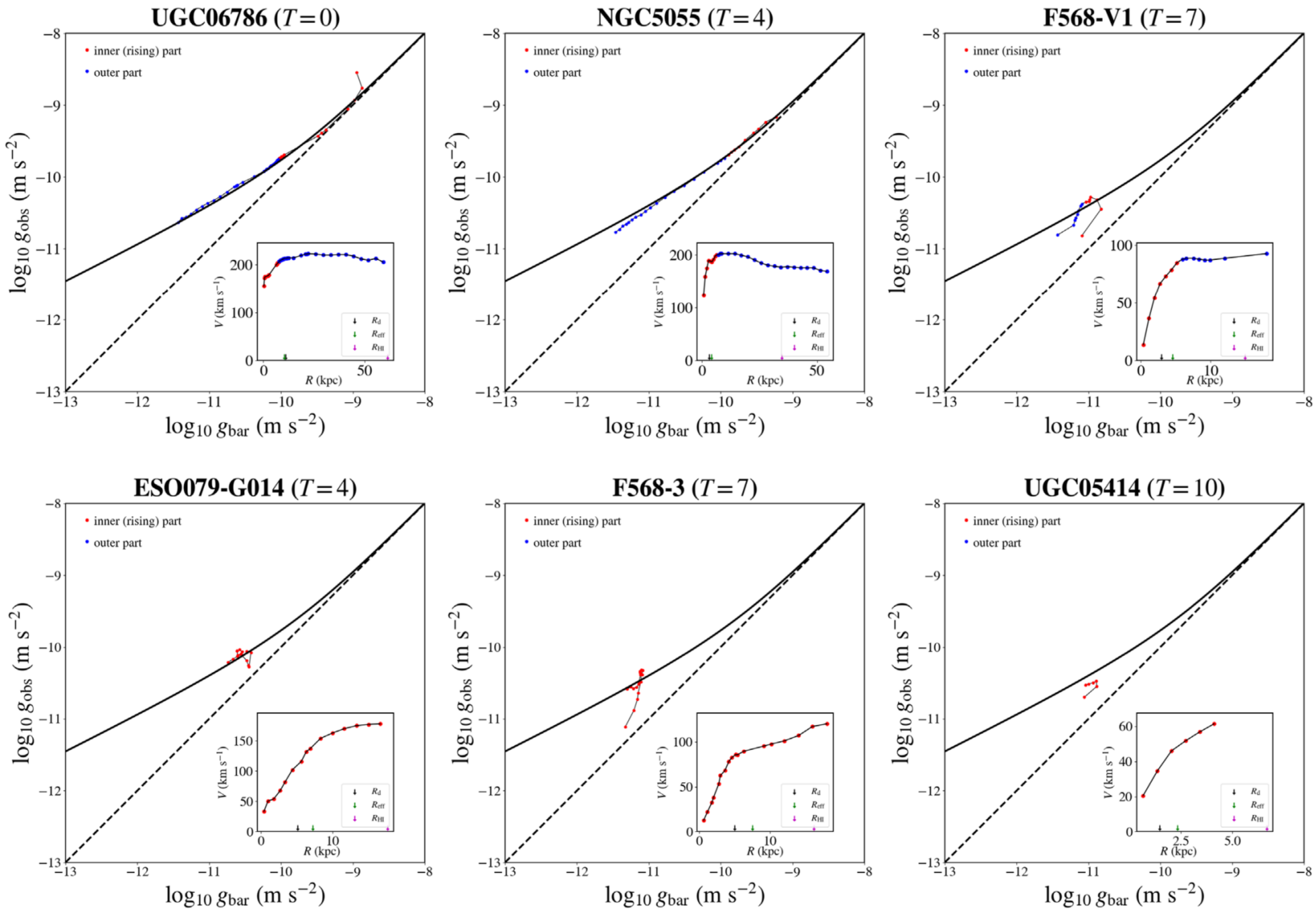
Theoretical predictions of AQUAL (Bekenstein & Milgrom 1984) & QUMOND (Milgrom 2010): numerical solutions by **Chae & Milgrom (2022)**



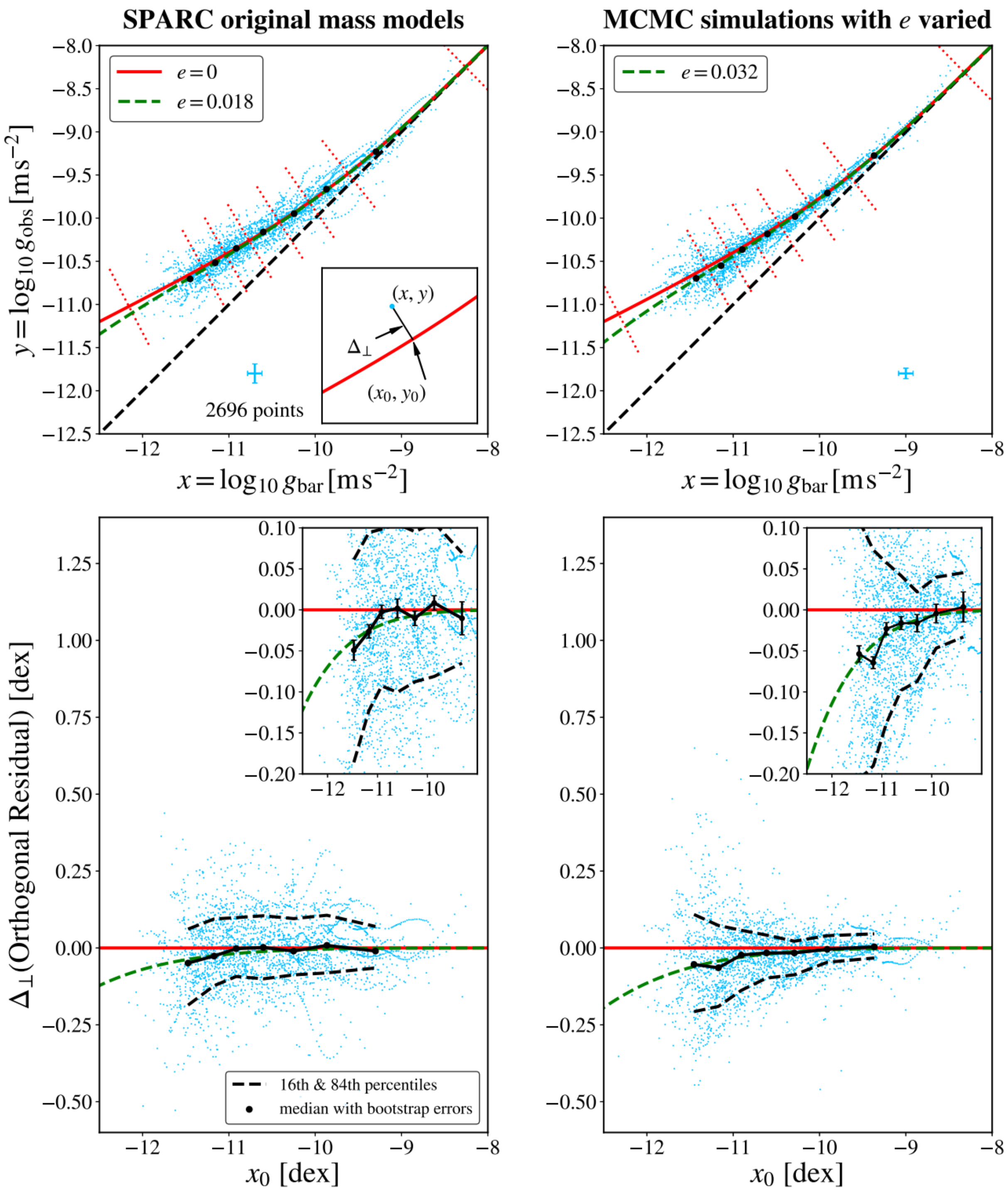


a: disk scale length (for the MN disk)

$a_M = \sqrt{GM/a_0}$: MOND radius



UGC06786 ($T=0$)
NGC5055 ($T=4$)
F568-V1 ($T=7$)
ESO079-G014 ($T=4$)
F568-3 ($T=7$)
UGC05414 ($T=10$)
inner (rising) part
outer part
$\log_{10} g_{\rm obs}$ (m s^{-2})
$\log_{10} g_{\rm bar}$ (m s^{-2})
V (km s^{-1})
R (kpc)
$R_{\rm d}$
$R_{\rm eff}$
$R_{\rm HI}$



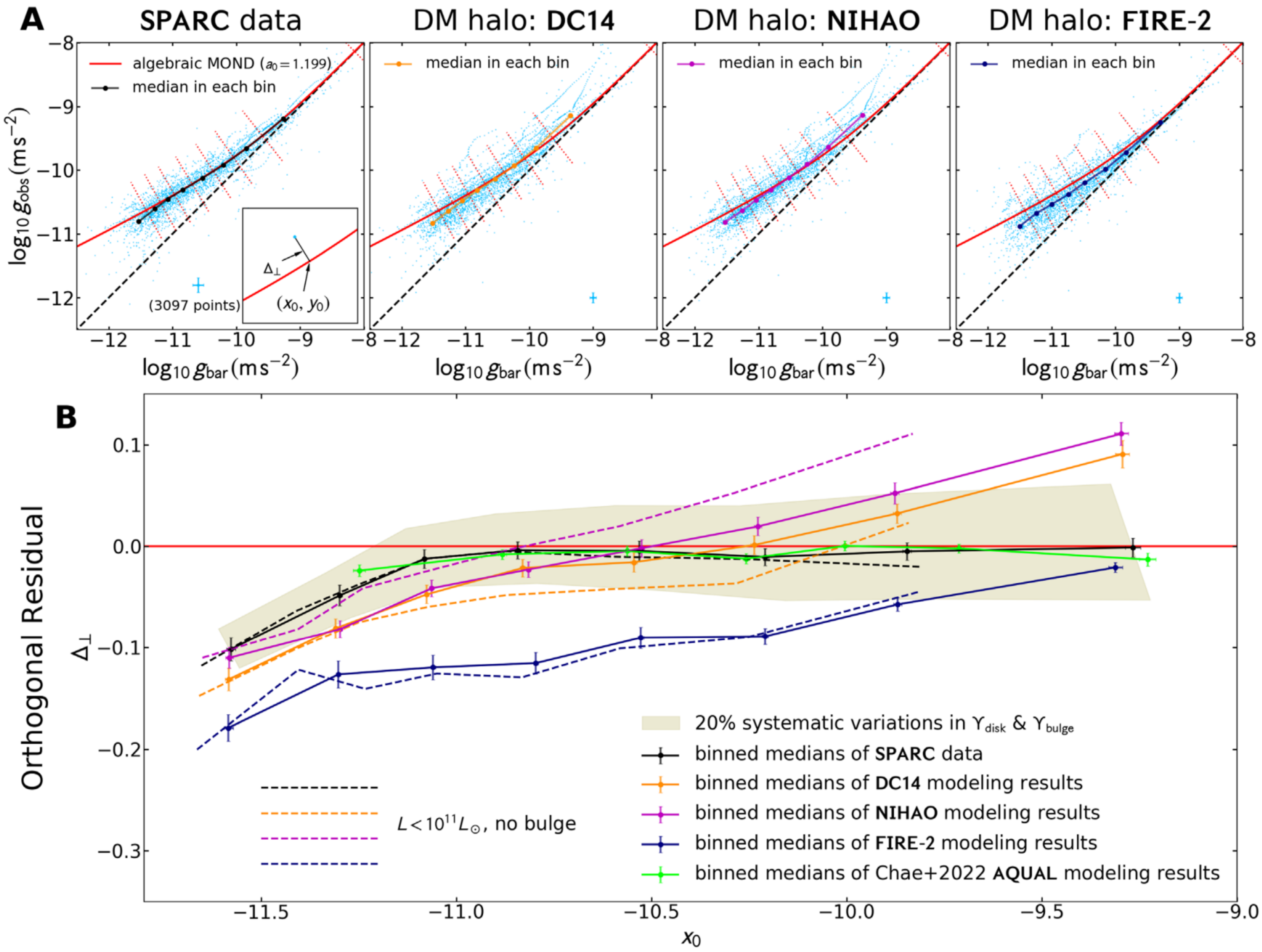
Chae et al. (2020):

Orthogonal residuals showing downward deviations in the radial acceleration relation

Bayesian modeling of the rotation velocity data V_{rot} with modified gravity or standard gravity + DM

$$p(\boldsymbol{\beta}) = \mathcal{L} \times \prod_k \Pr(\beta_k),$$

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{j=1}^{N}\left[\left(\frac{V_{\mathrm{rot}}(i;\, R_j) - V_{\mathrm{mod}}(\boldsymbol{\beta};\, R_j)}{\sigma_{V_{\mathrm{rot}}(i;R_j)}}\right)^2 + \ln\left(2\pi\sigma^2_{V_{\mathrm{rot}}(i;R_j)}\right)\right],$$



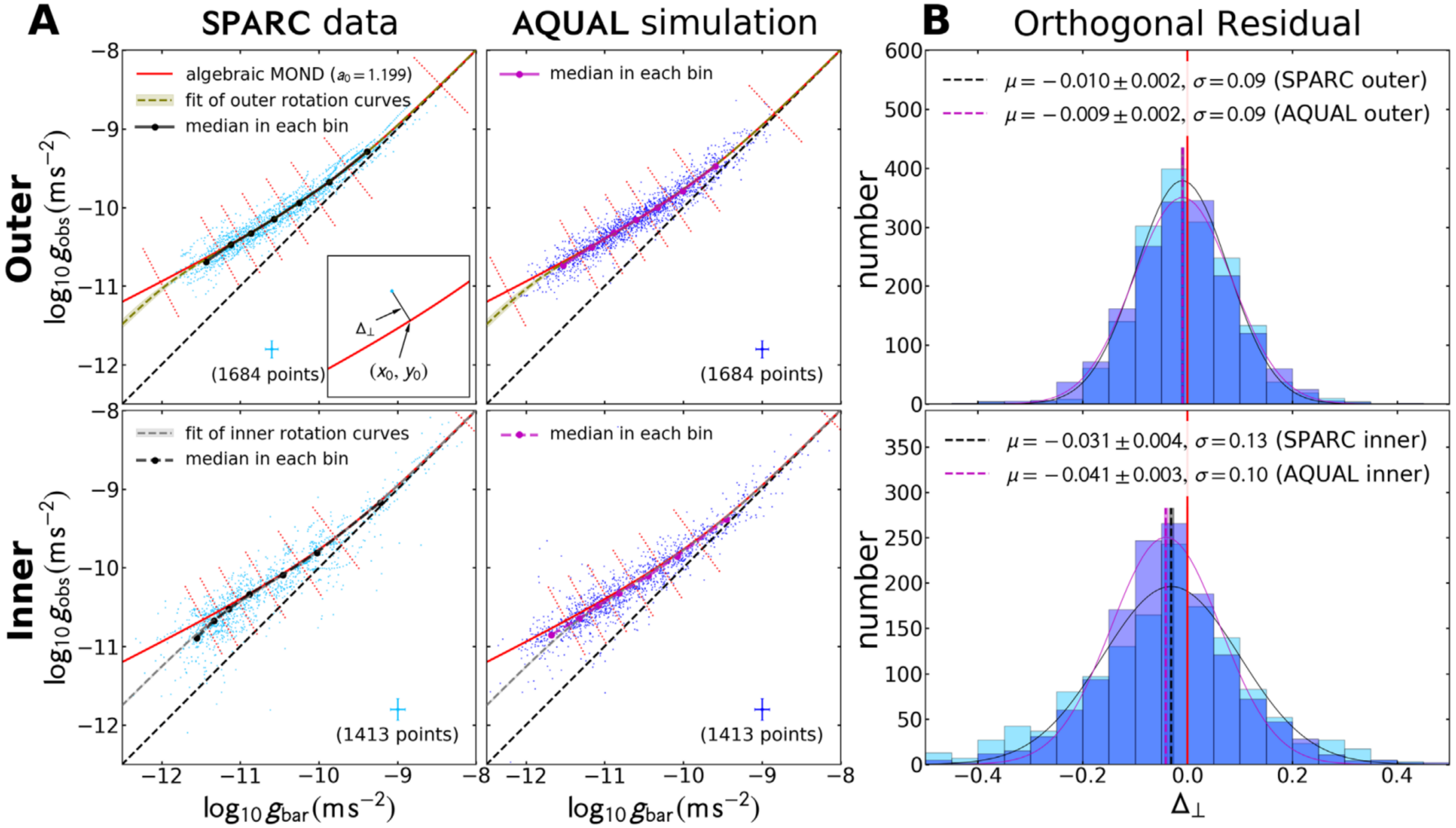
LCDM models can roughly mimic the trend of the RAR.

AQUAL simulation

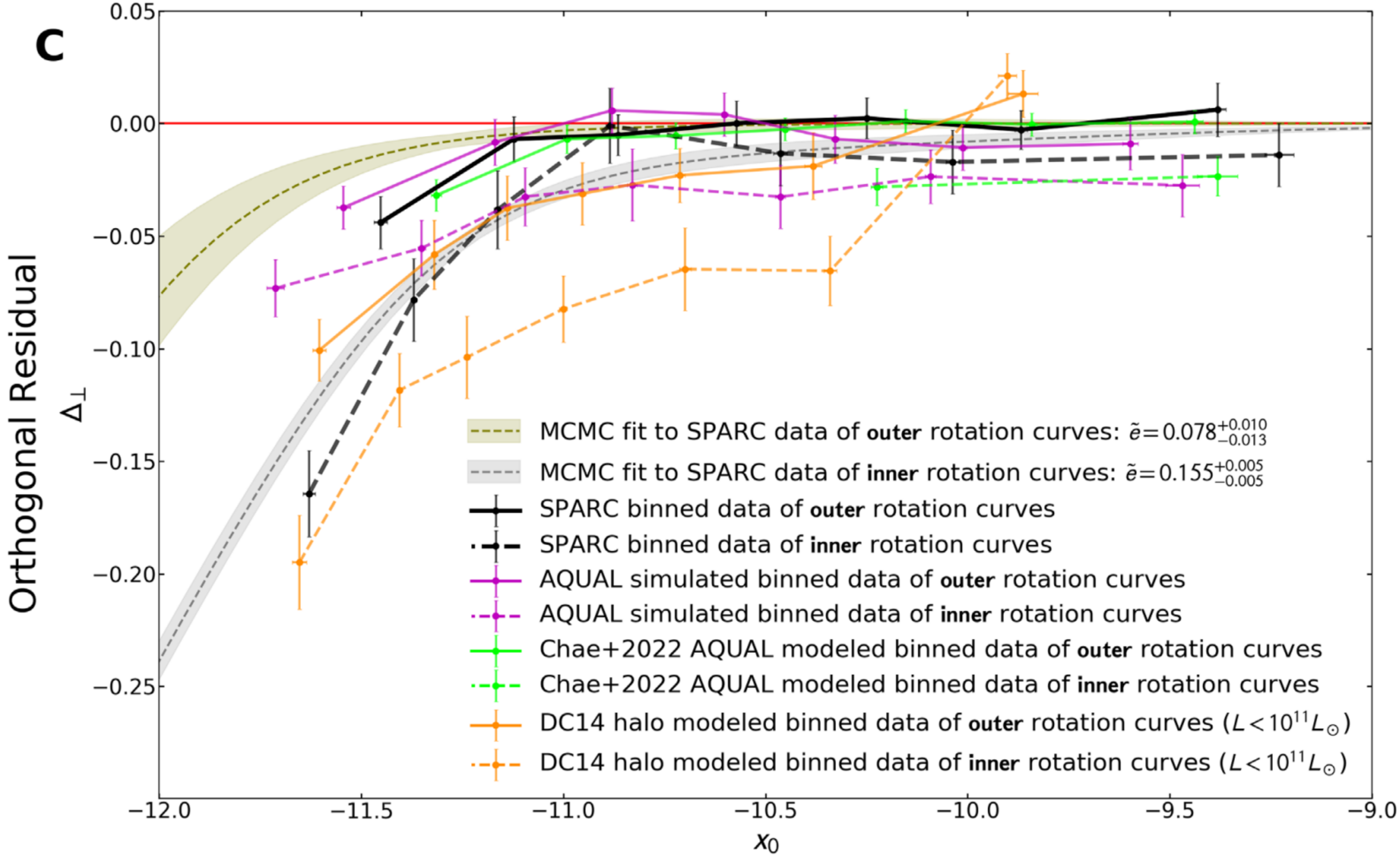
Solve the AQUAL equation with the Chae & Milgrom (2022) numerical solver based on the Milgrom (1986).

Predict (g_{N}, g) on the acceleration plane for the SPARC galaxies.

Compare the predicted (g_{N}, g) with the SPARC data for the outer part, the inner part, and both together.



A
SPARC data
AQUAL simulation
B
Orthogonal Residual
Outer
Inner
algebraic MOND ($a_0 = 1.199$)
fit of outer rotation curves
median in each bin
fit of inner rotation curves
$\Delta_\perp$
(x_0, y_0)
(1684 points)
(1413 points)
$\log_{10} g_{obs} (\mathrm{m\,s^{-2}})$
$\log_{10} g_{bar} (\mathrm{m\,s^{-2}})$
$\mu = -0.010 \pm 0.002$, $\sigma = 0.09$ (SPARC outer)
$\mu = -0.009 \pm 0.002$, $\sigma = 0.09$ (AQUAL outer)
$\mu = -0.031 \pm 0.004$, $\sigma = 0.13$ (SPARC inner)
$\mu = -0.041 \pm 0.003$, $\sigma = 0.10$ (AQUAL inner)
number

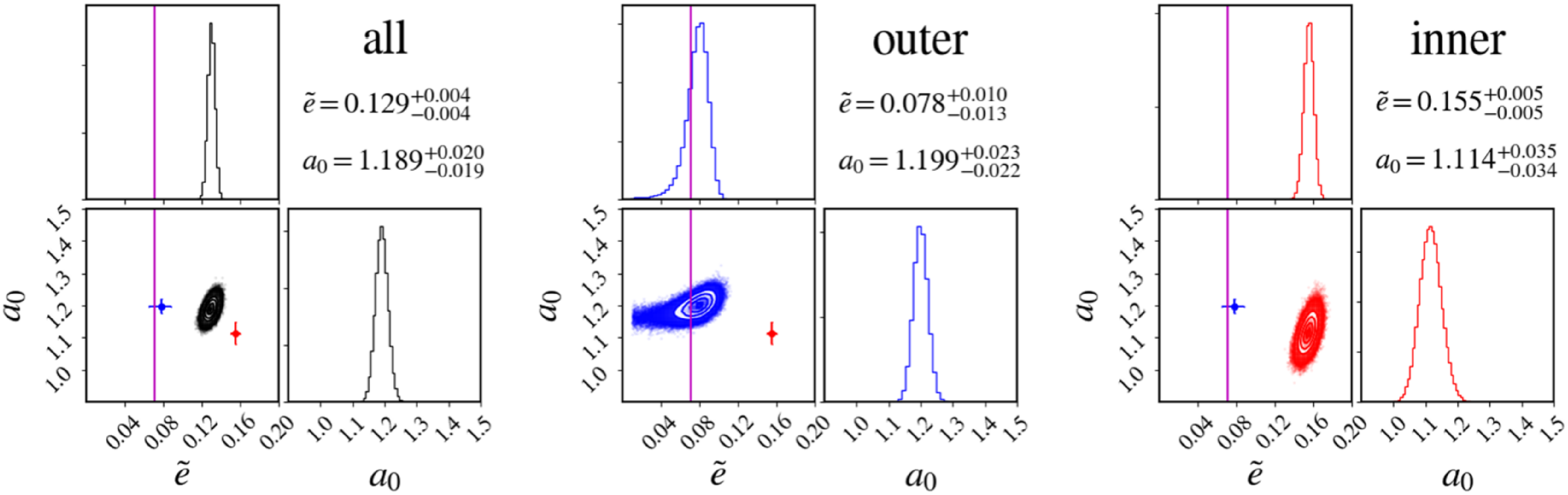


c
Orthogonal Residual
$\Delta_\perp$
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
−12.0
−11.5
−11.0
−10.5
−10.0
−9.5
−9.0
x_0
MCMC fit to SPARC data of **outer** rotation curves: $\tilde{e}=0.078^{+0.010}_{-0.013}$
MCMC fit to SPARC data of **inner** rotation curves: $\tilde{e}=0.155^{+0.005}_{-0.005}$
SPARC binned data of **outer** rotation curves
SPARC binned data of **inner** rotation curves
AQUAL simulated binned data of **outer** rotation curves
AQUAL simulated binned data of **inner** rotation curves
Chae+2022 AQUAL modeled binned data of **outer** rotation curves
Chae+2022 AQUAL modeled binned data of **inner** rotation curves
DC14 halo modeled binned data of **outer** rotation curves ($L<10^{11}L_\odot$)
DC14 halo modeled binned data of **inner** rotation curves ($L<10^{11}L_\odot$)

Fitting the RAR data with a numerically derived fitting function of $(e_{\rm N}, a_0)$ where $e_{\rm N} \equiv \frac{g_{\rm N,ext}}{a_0}$:

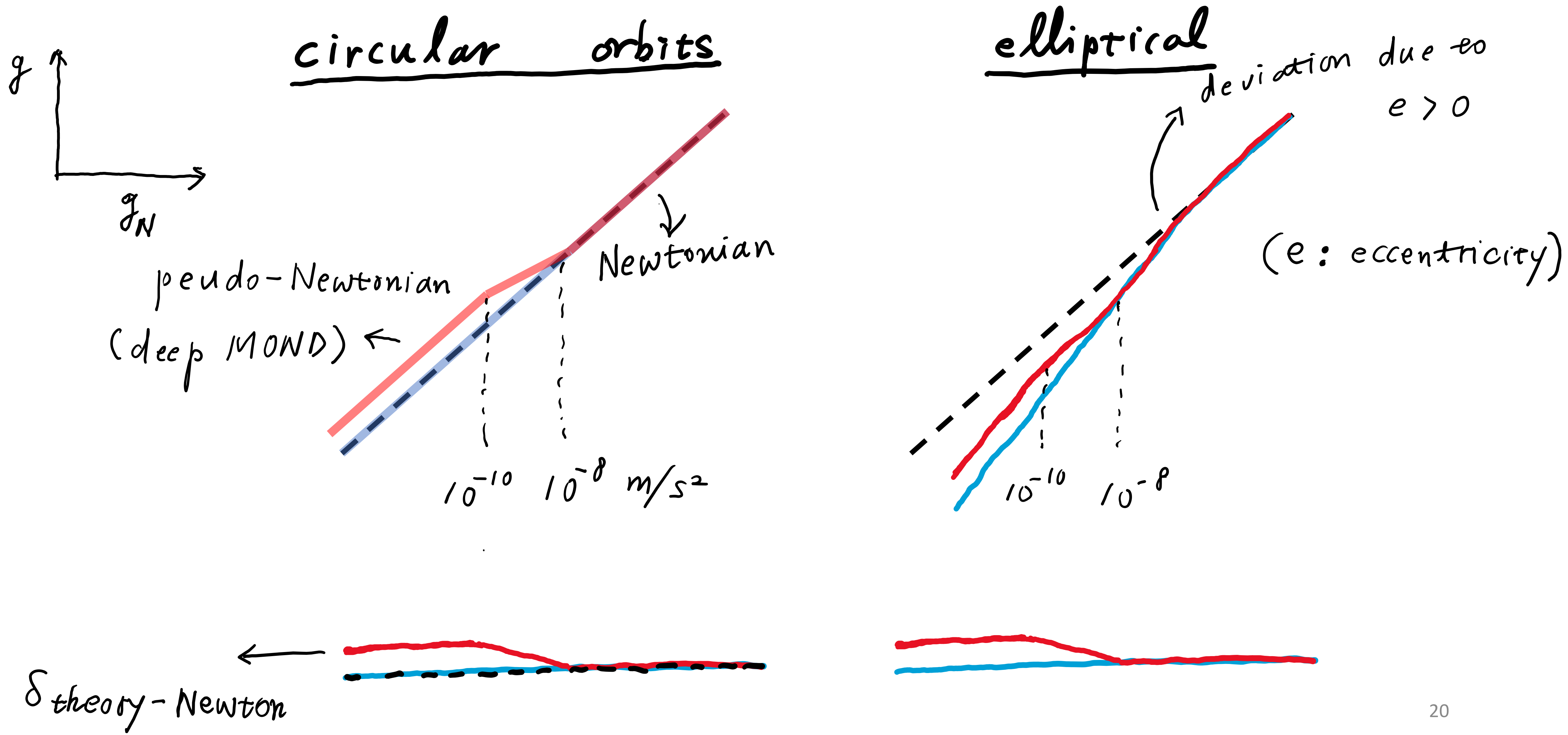
$$g_{\rm MOND} = g_{\rm bar}\nu(y_{1.1})\left[1 + \left\{\tanh\left(\frac{1.1 e_{\rm N}}{g_{\rm bar}/a_0}\right)\right\}^{1.2} \frac{\hat{\nu}(y_{1.1})}{3}\right],$$

$(\tilde{e} \equiv \sqrt{e_{\rm N}})$



- The fitted value of $\tilde{e}$ is acceptable only when the outer part data are fitted. AQUAL is preferred over QUMOND (Chae et al. 2022).
- There is a clear difference between the outer part and the inner part: 6.9σ
- The difference is expected by the modified Poisson equation of AQUAL! A truly surprising result!

Theoretical predictions for wide binaries under the Galactic external field



Observed projected quantities v_p and s: deprojection to the 3D quantities v and r.

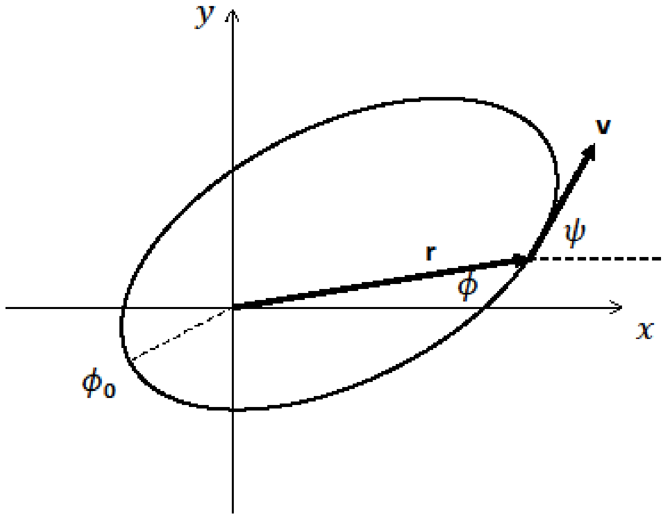
$$g = \frac{v^2}{r}$$

(kinematic accel.)

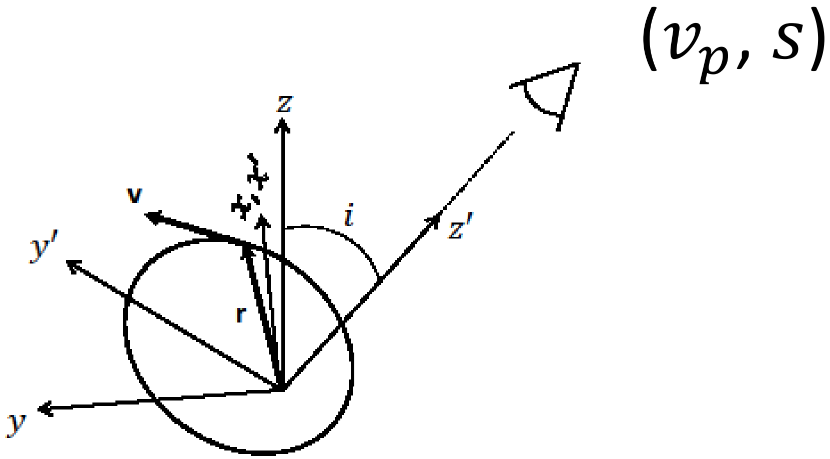
$$g_N = \frac{G M_{tot}}{r}$$

(Newtonian accel.)

M_{tot} : total mass including hidden companions

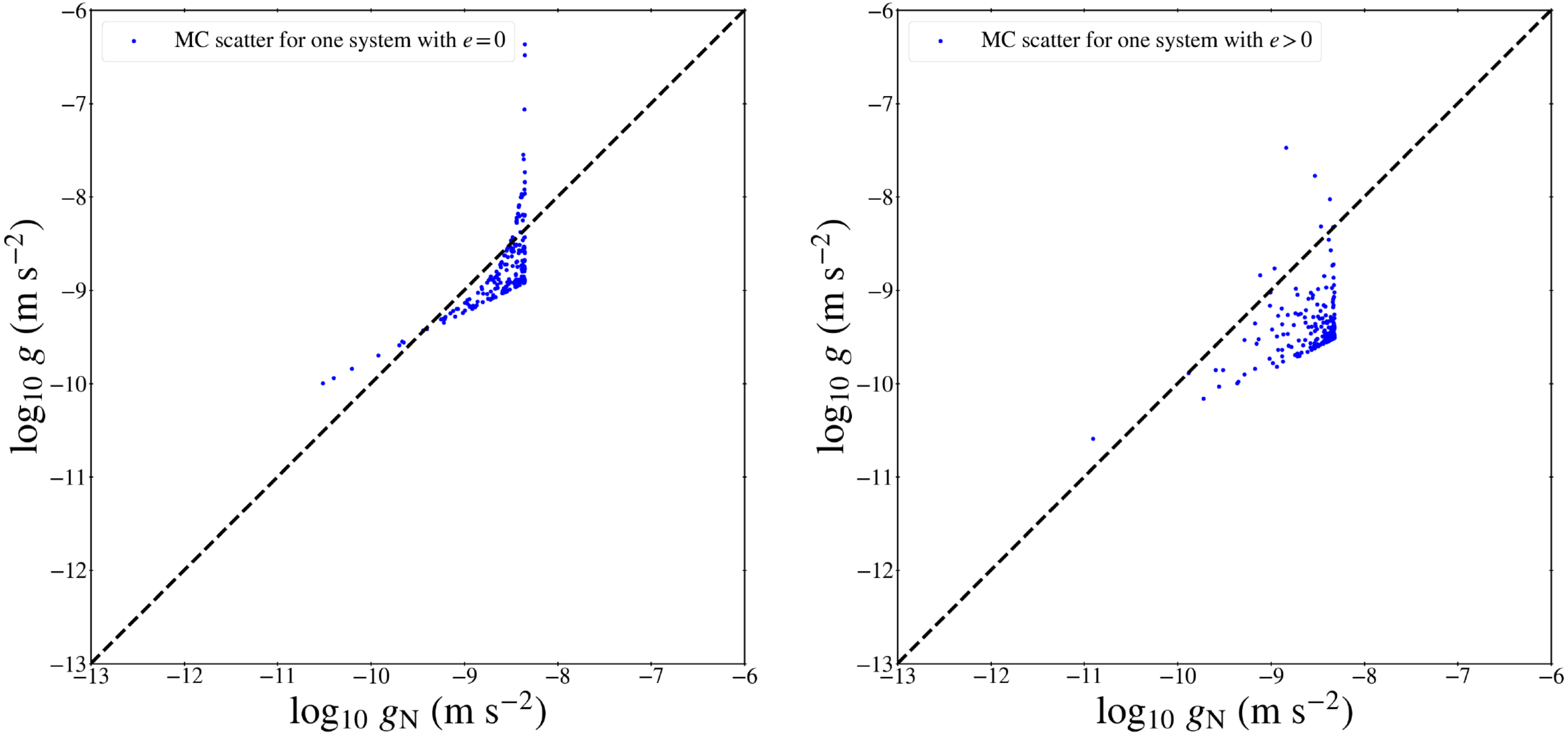


orbital plane
(face-on view)



observer's view
(3D geometry)

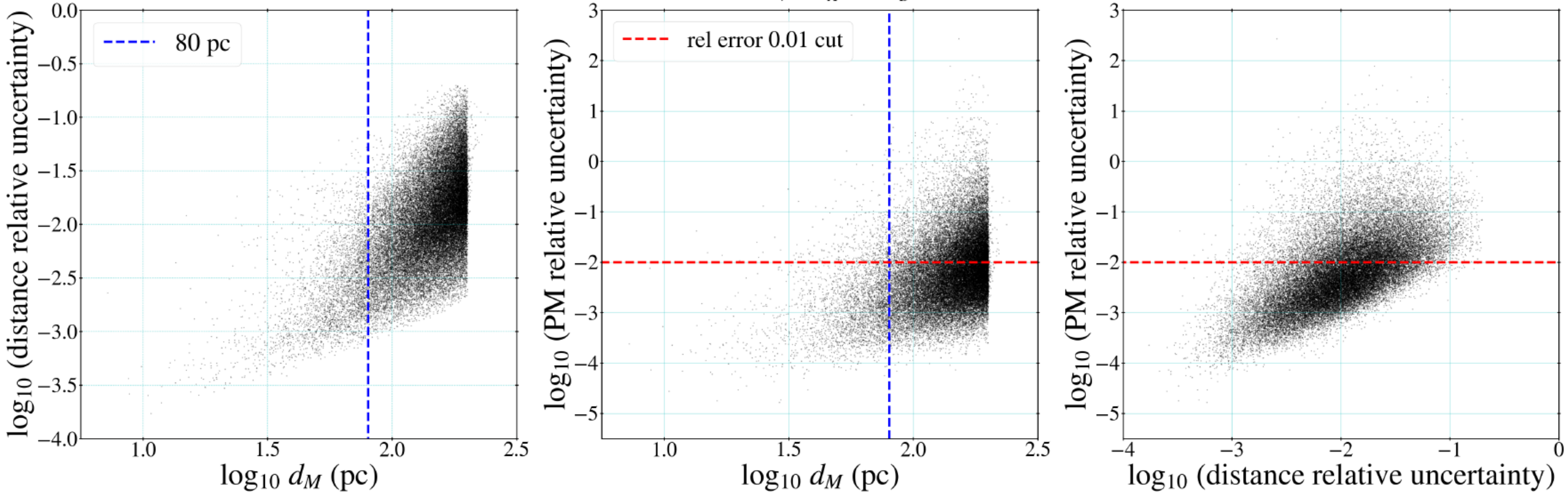
Possible outcomes of deprojection for individual binary systems: large scatters due to unknown inclination and orbital phase.
Thus, an individual system cannot be used to test gravity.
However, if a large number of binaries are used, gravity can be tested because statistical fluctuations will be averaged out.



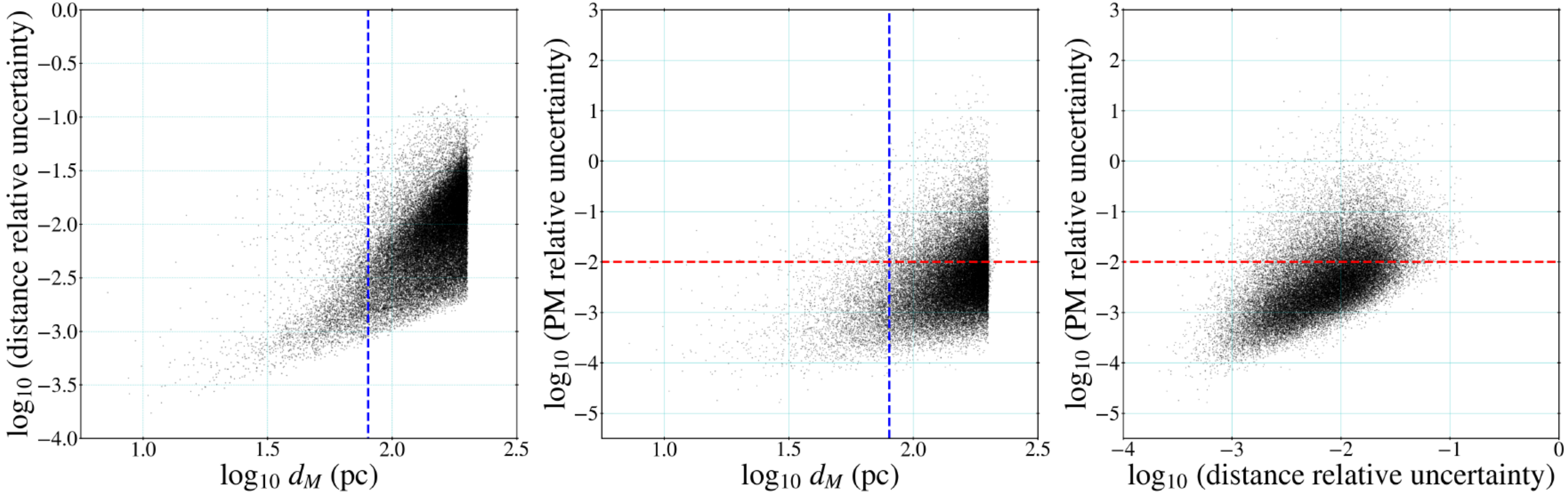
Sample selection from Gaia DR3

- Both stars belong to the main-sequence (the binary type is 'MSMS' according to the definition by El-Badry, Rix & Heintz (2021).
- $\mathcal{R} < 0.01$ where $\mathcal{R}$ is the chance alignment probability defined by El-Badry, Rix & Heintz (2021). removing fly-bys
- $|d_{\rm A} - d_{\rm B}| < 3\sqrt{\sigma^2_{d_{\rm A}} + \sigma^2_{d_{\rm B}}}$ (distances of two components agree within 3σ).
- Relative errors of all PM components for each binary are all smaller than 0.01. set by < 80 pc sample
- The sky-projected separation is in the range $0.2 < s < 30$ kau.
- Absolute magnitudes for both components are within a 'clean range' $4 < M_G < 14$ or a 'strict range' $4 < M_G < 12$.

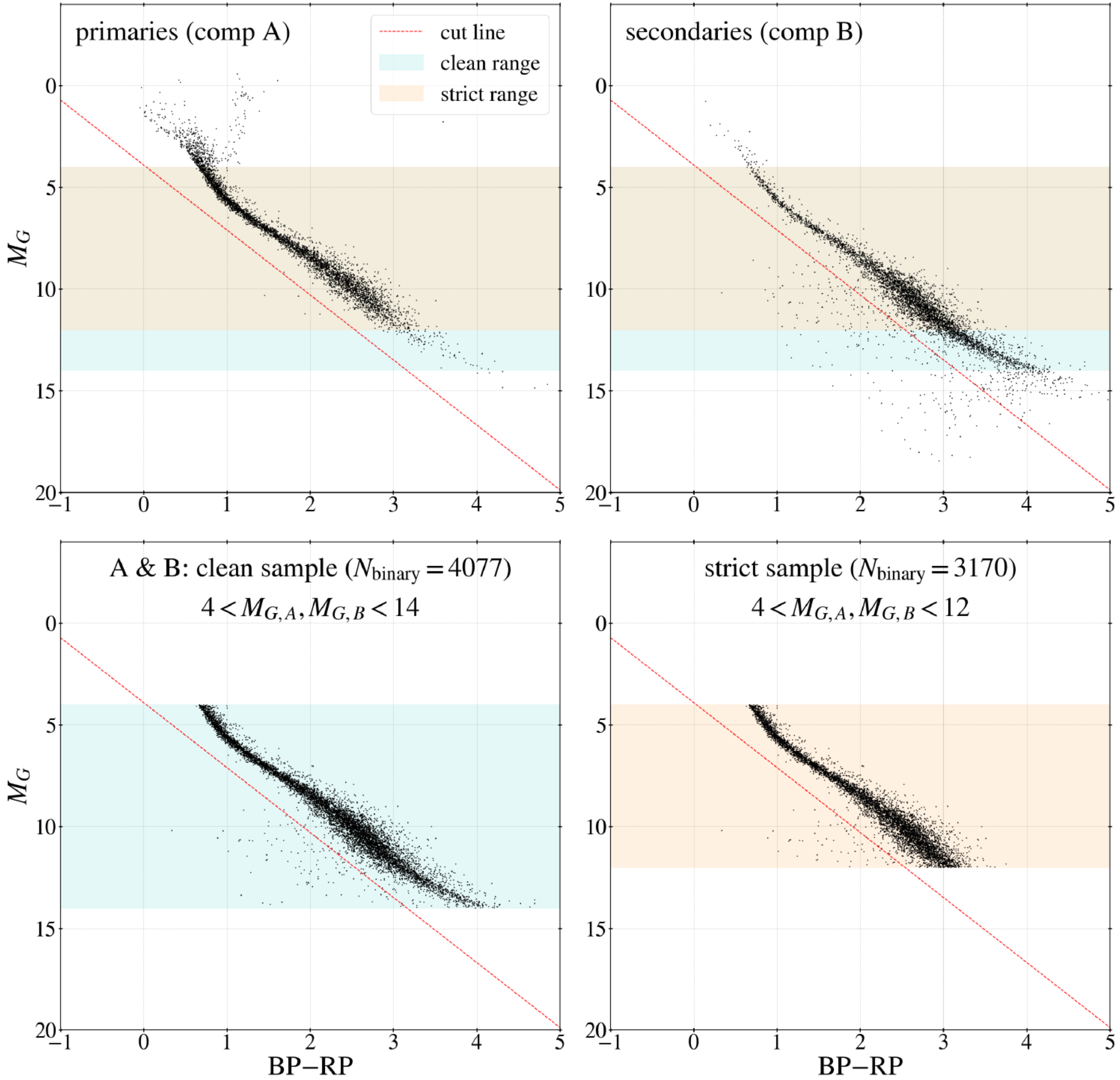
$0.2 < s < 30$ kau, $|d_A - d_B| < 3\sqrt{\sigma_{d_A}^2 + \sigma_{d_B}^2}$, and $4 < M_{G,A}, M_{G,B} < 14$



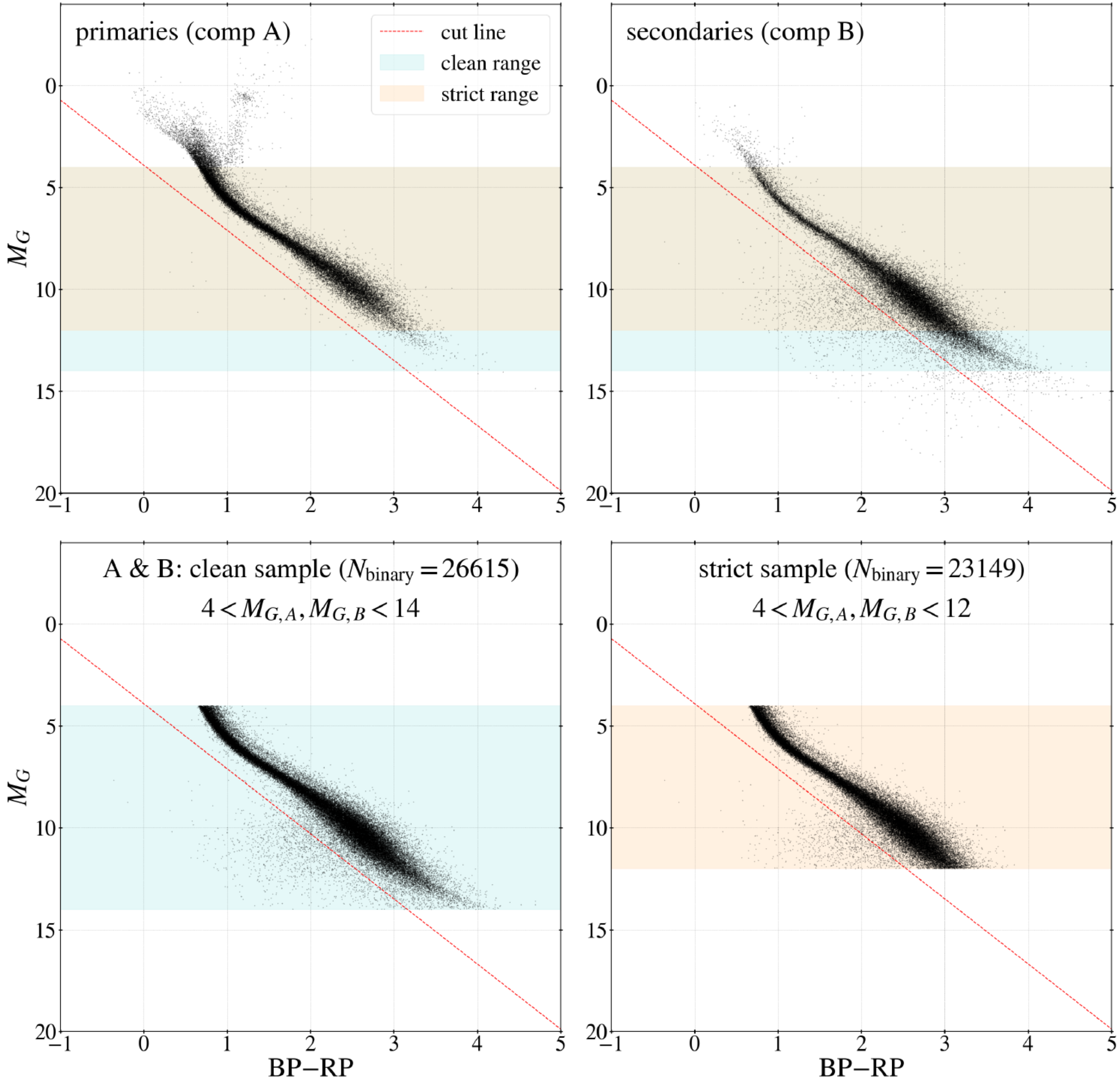
$4 < M_{G,A}, M_{G,B} < 12$



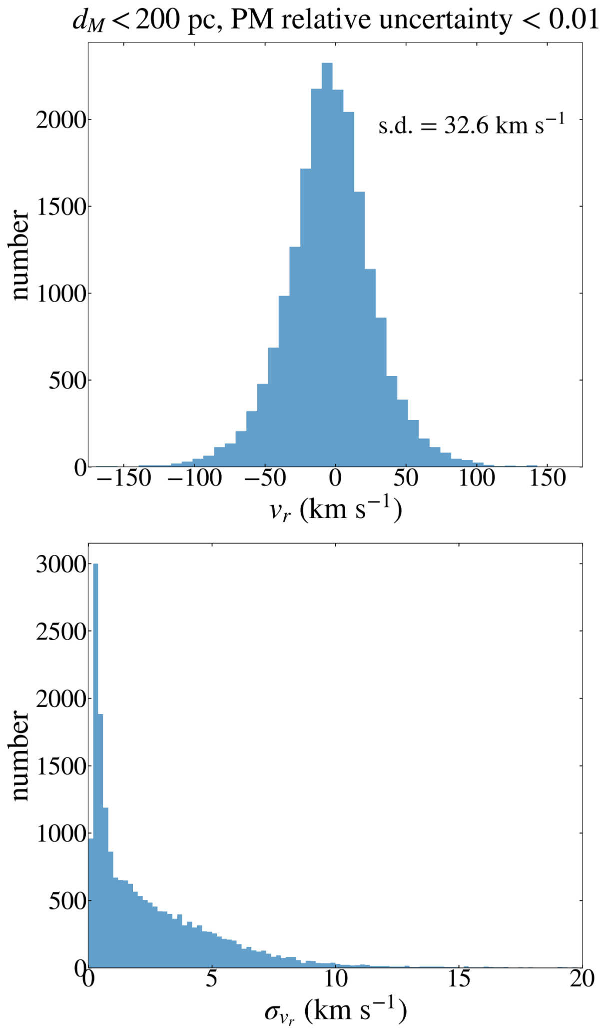
$d_M < 80$ pc, $0.2 < s < 30$ kau, $|d_A - d_B| < 3\sqrt{\sigma_{d_A}^2 + \sigma_{d_B}^2}$, PM relative uncertainty < 0.01

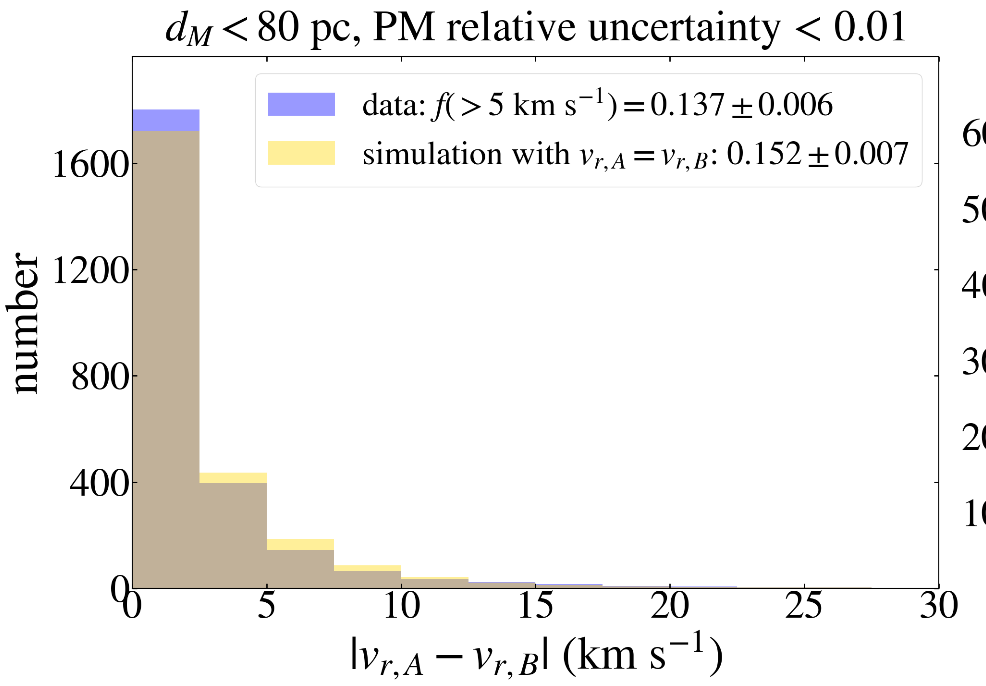


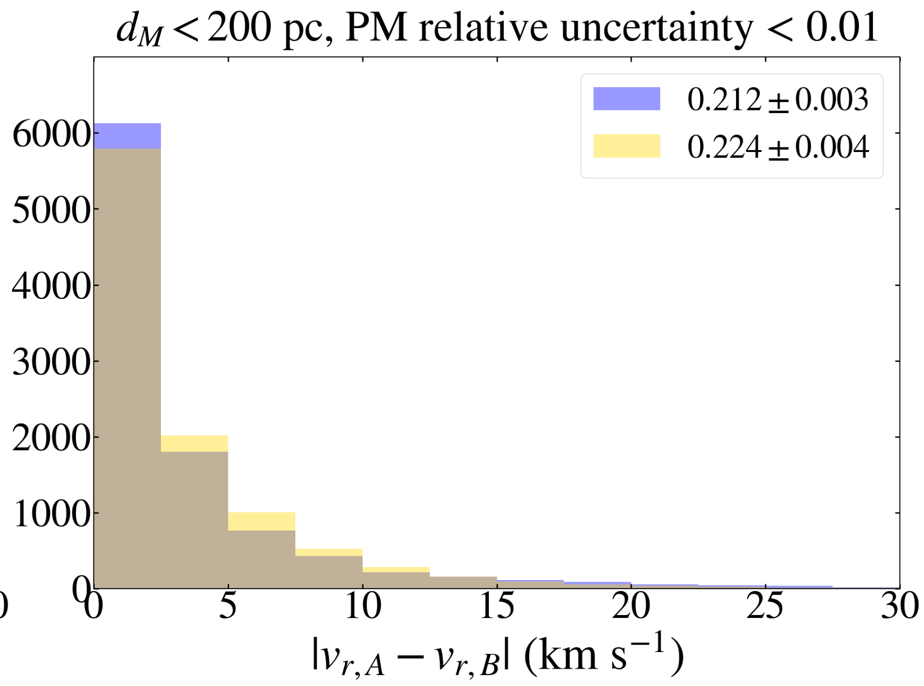
$d_M < 200$ pc, $0.2 < s < 30$ kau, $|d_A - d_B| < 3\sqrt{\sigma_{d_A}^2 + \sigma_{d_B}^2}$, PM relative uncertainty < 0.01



Distribution of relative radial velocities: Confirm that there are no/little fly-bys.

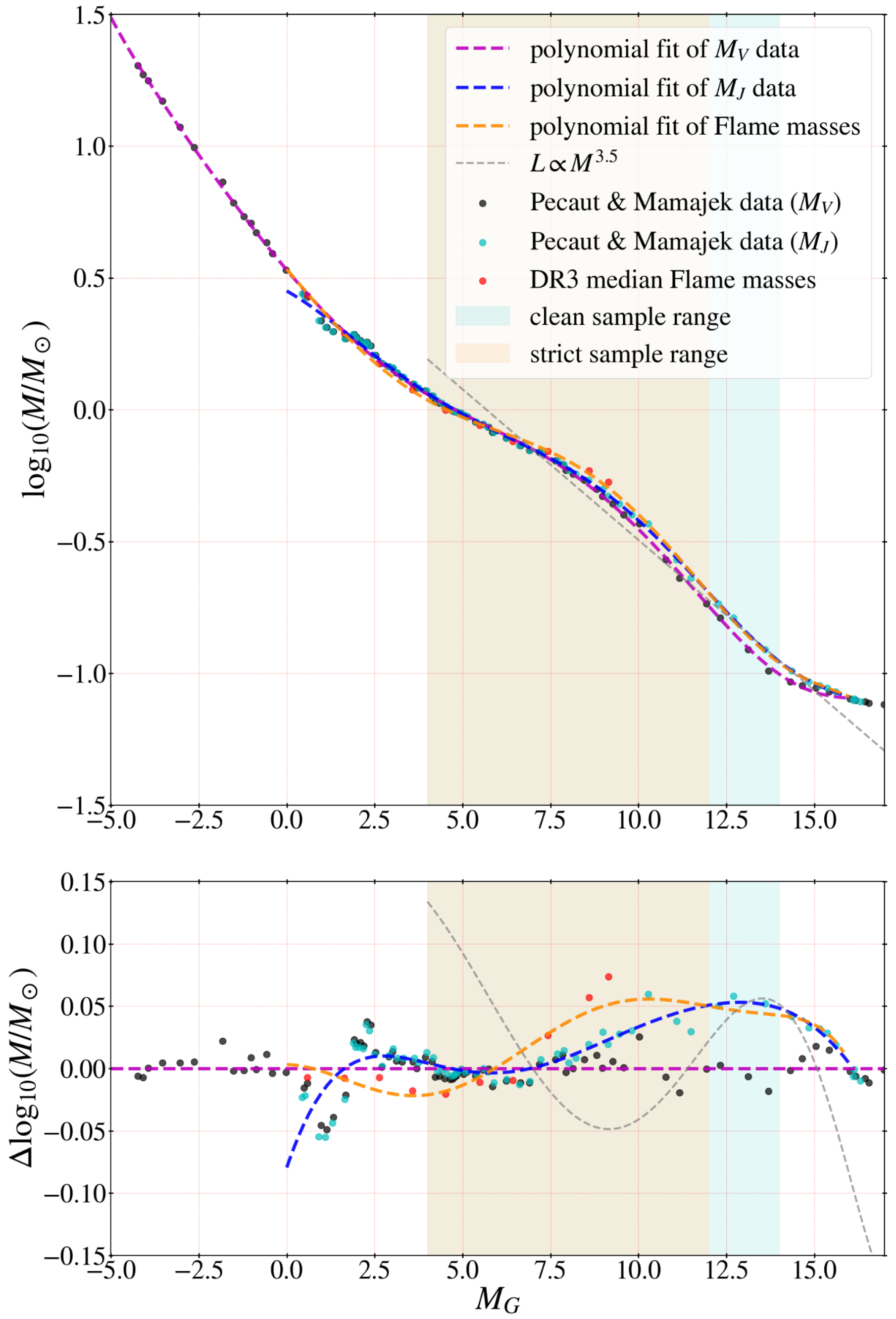


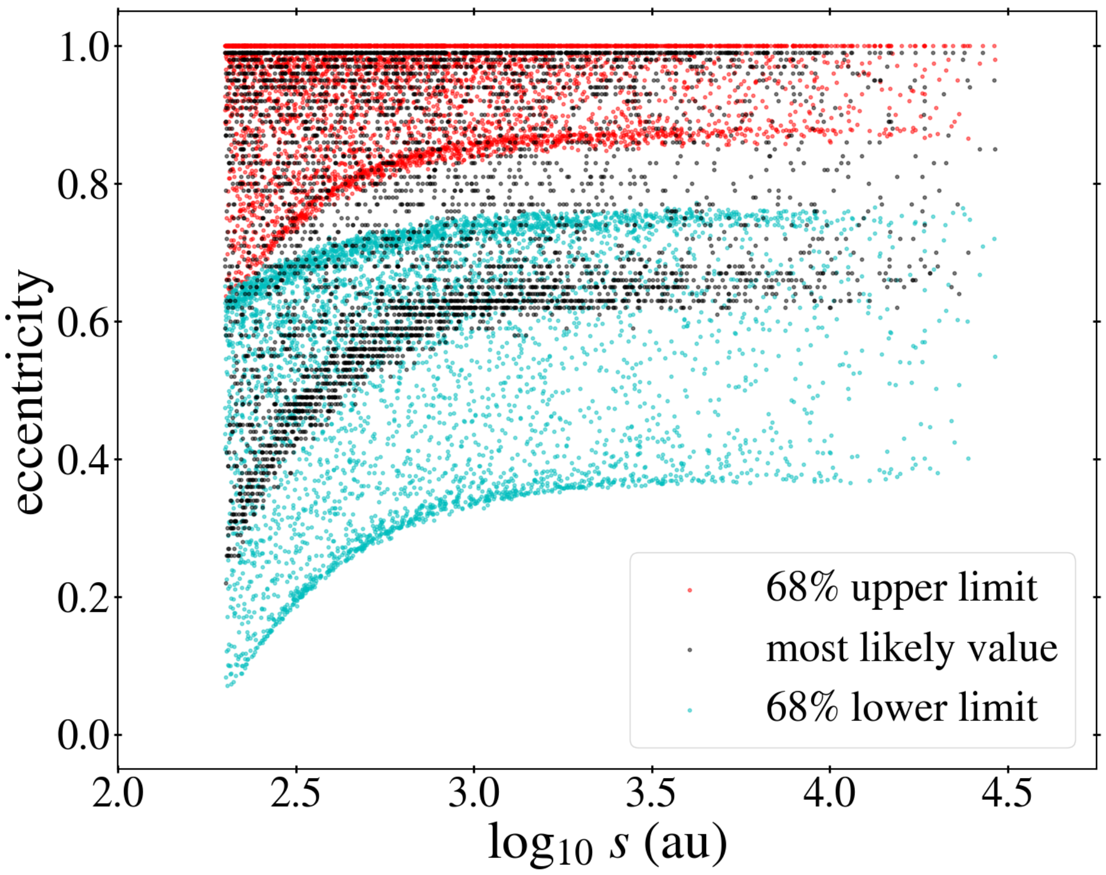




Key ingredients of wide binary test

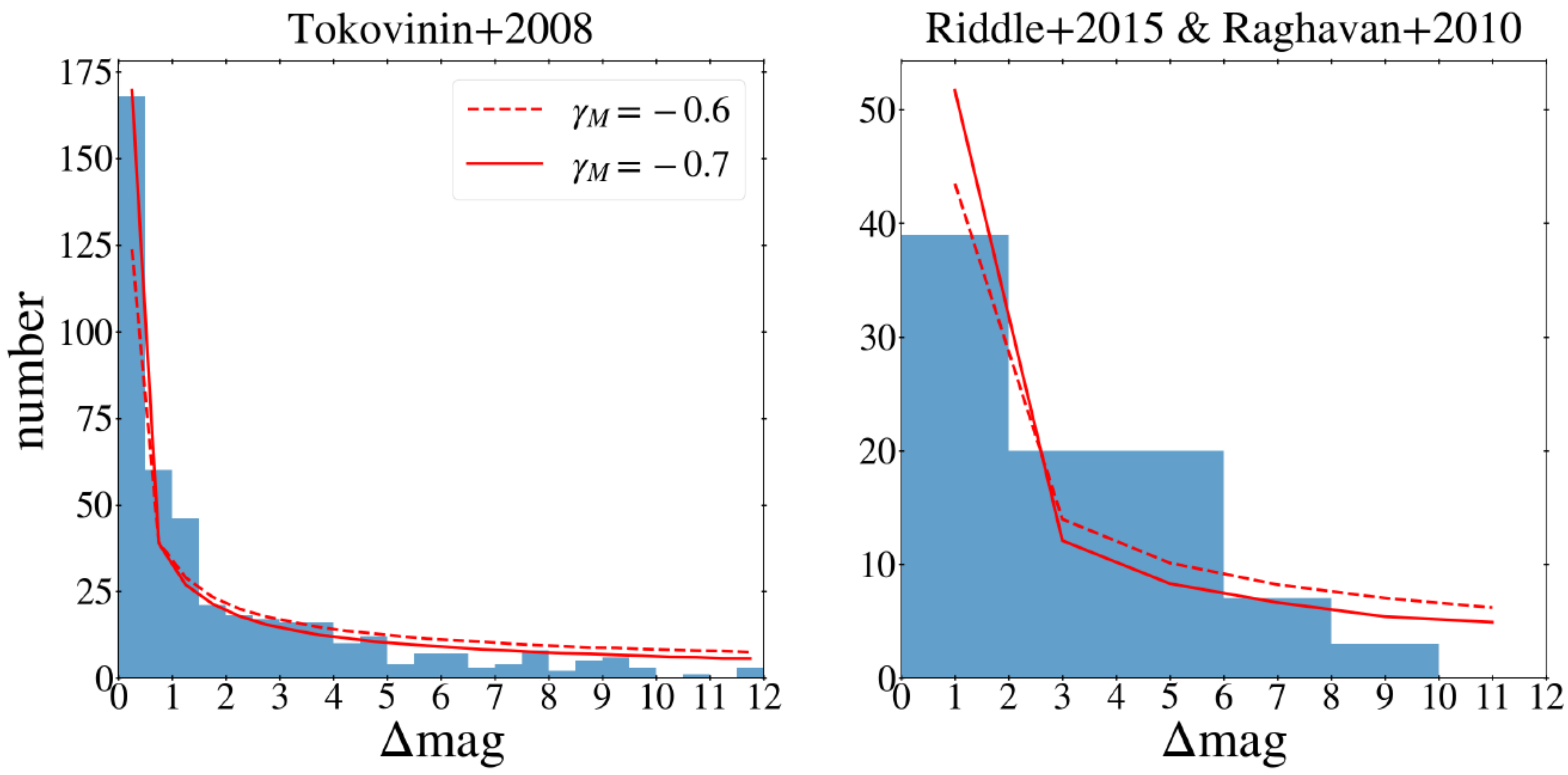
- Mass-magnitude relation: how to assign mass to the observed magnitude
- High-order multiplicity: hidden components contribute to the system mass thus g_{N}. f_{multi} = fraction of binaries having any hidden close companion(s).
- Eccentricities: the deprojection depends critically on the eccentricity





eccentricities from Hwang et al. (2022)

Masses of hidden close companions are statistically assigned by an empirical distribution of magnitude differences assuming that the observed luminosity is the combination of the observed and hidden components.



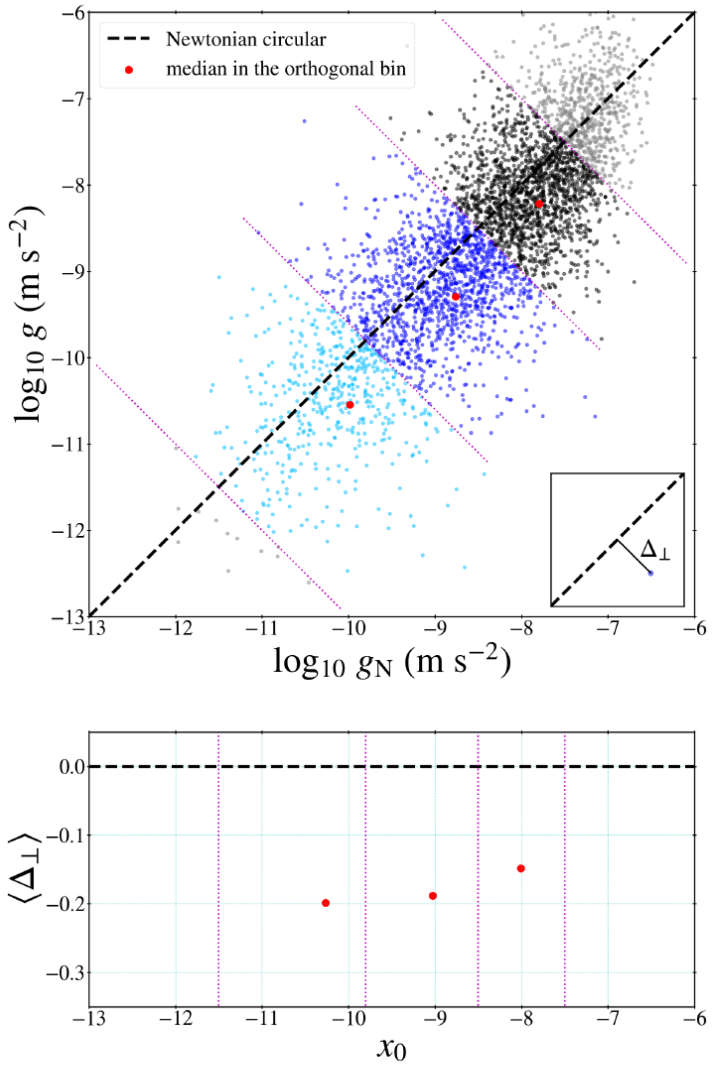
Calibration of high-order multiplicity f_{multi}

- f _multi is calibrated so that $\delta_{\text{theory}-\text{Newton}} = 0$ at $10^{-8}\ \text{m s}^{-2}$ in a binary sample.

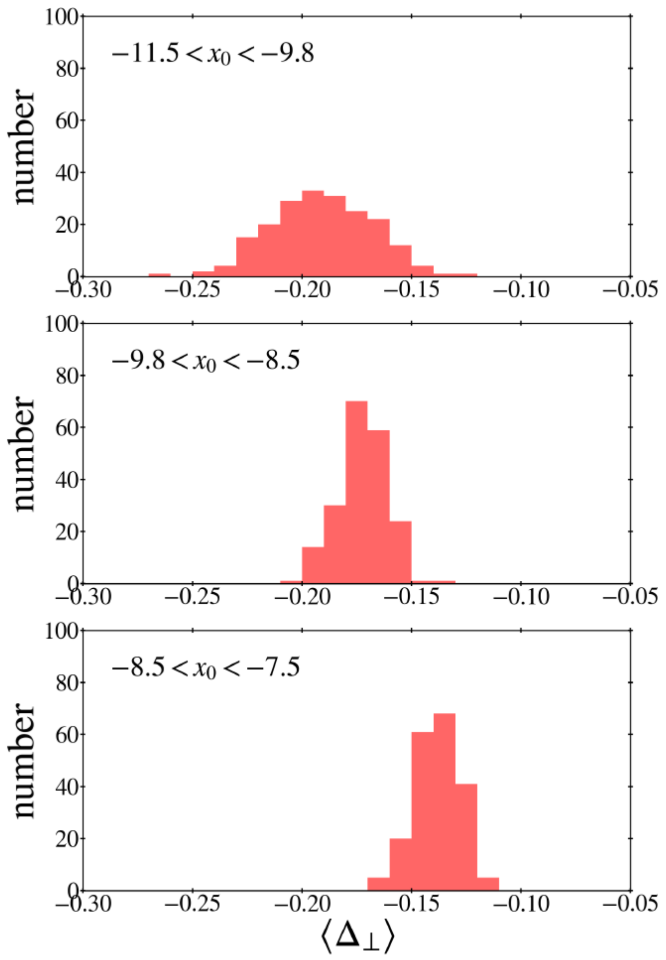
- Thus, f _multi is sample-specific as it should be.

Monte Carlo (MC) deprojection example

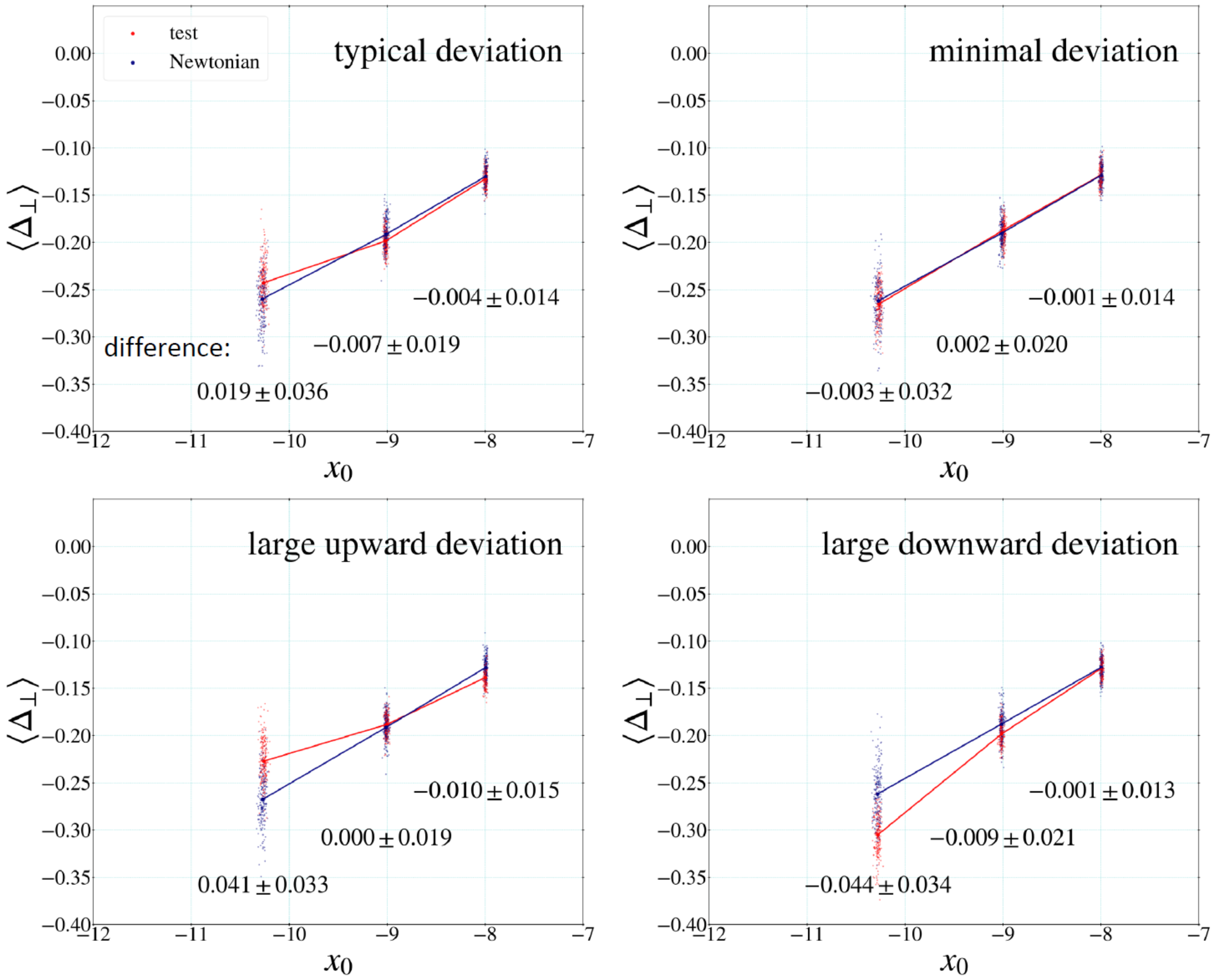
One Monte Carlo deprojection set



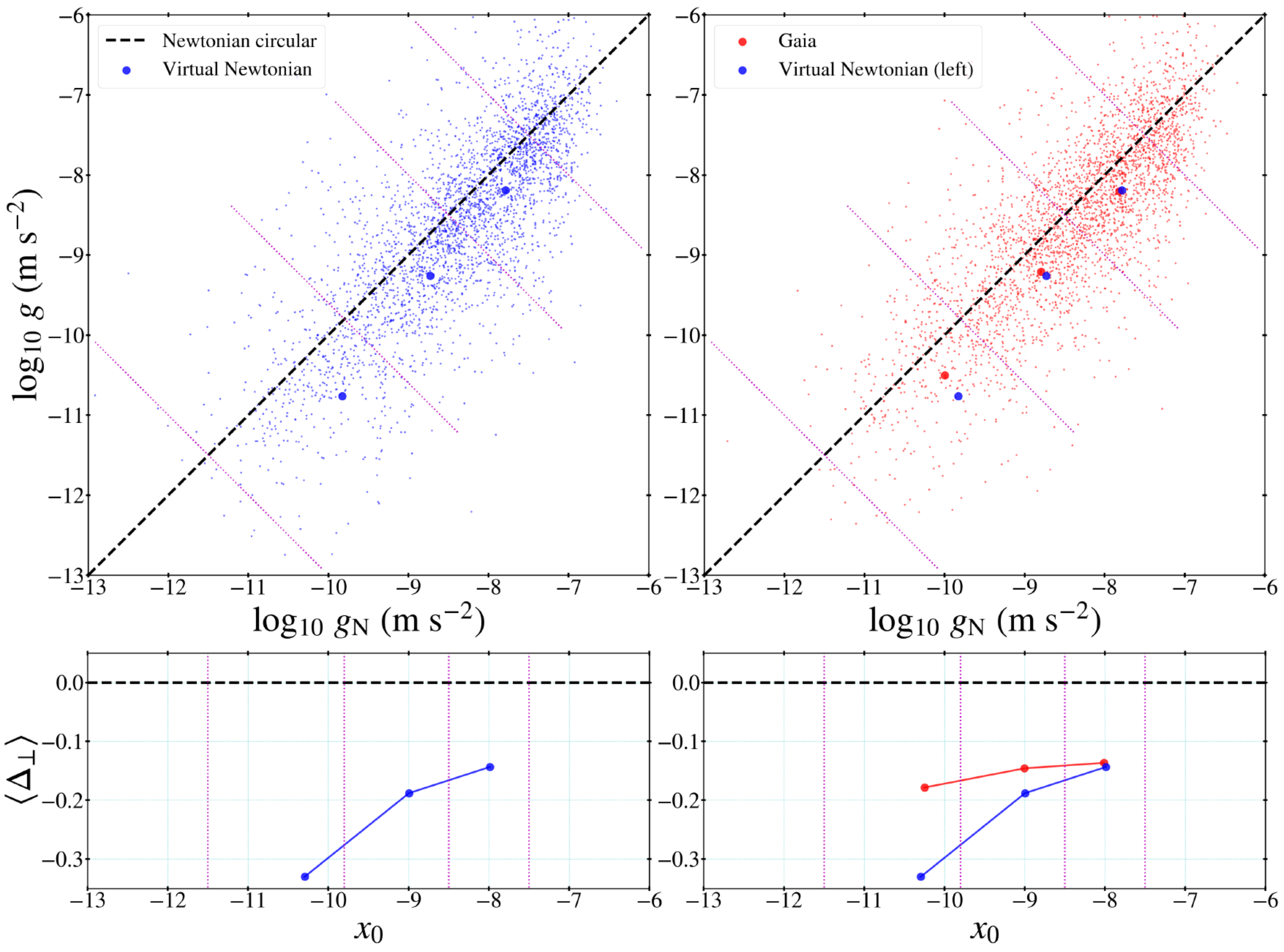
distribution in an ensemble of Monte Carlo sets



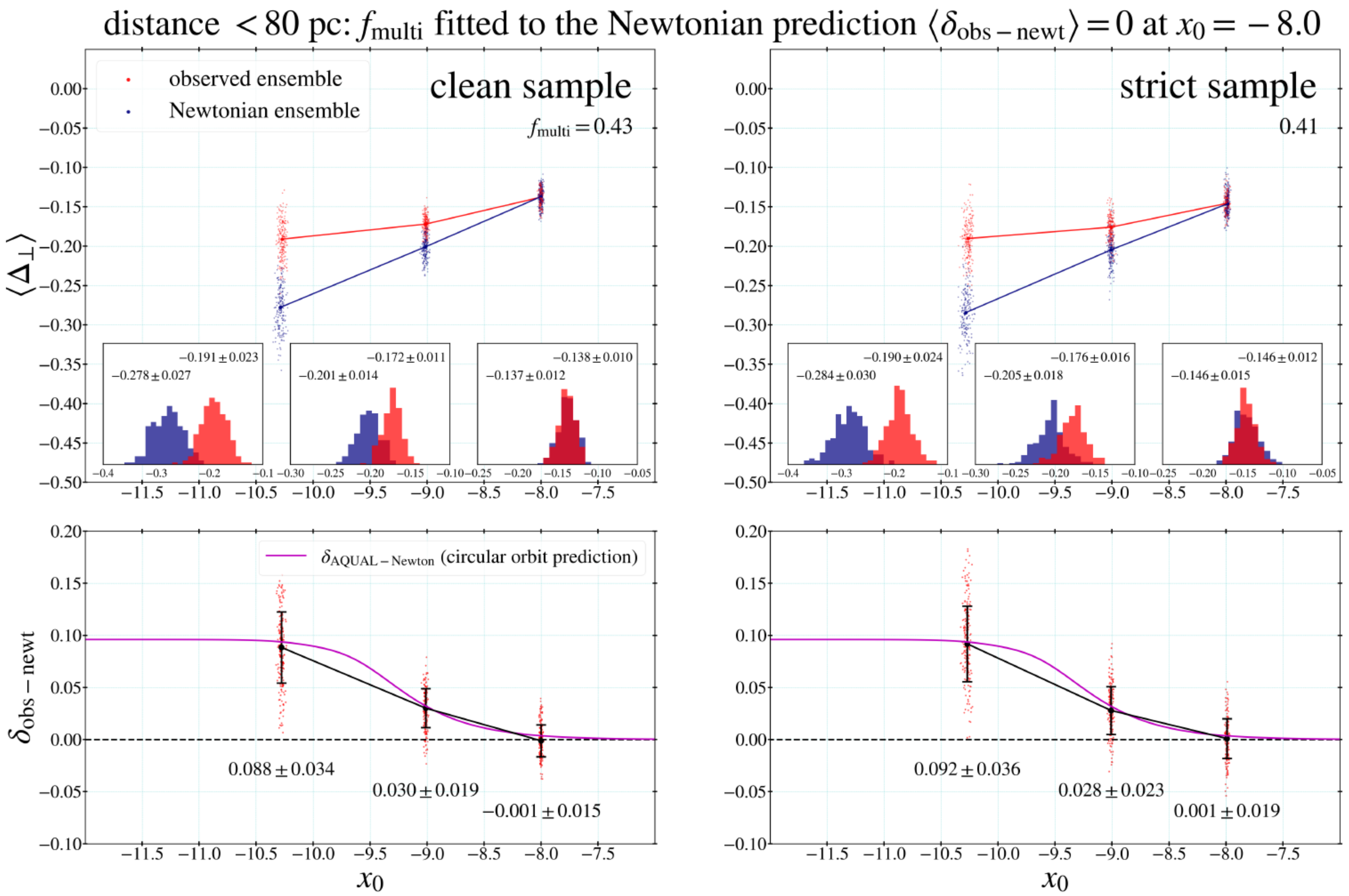
Validation with virtual Newtonian proper motions



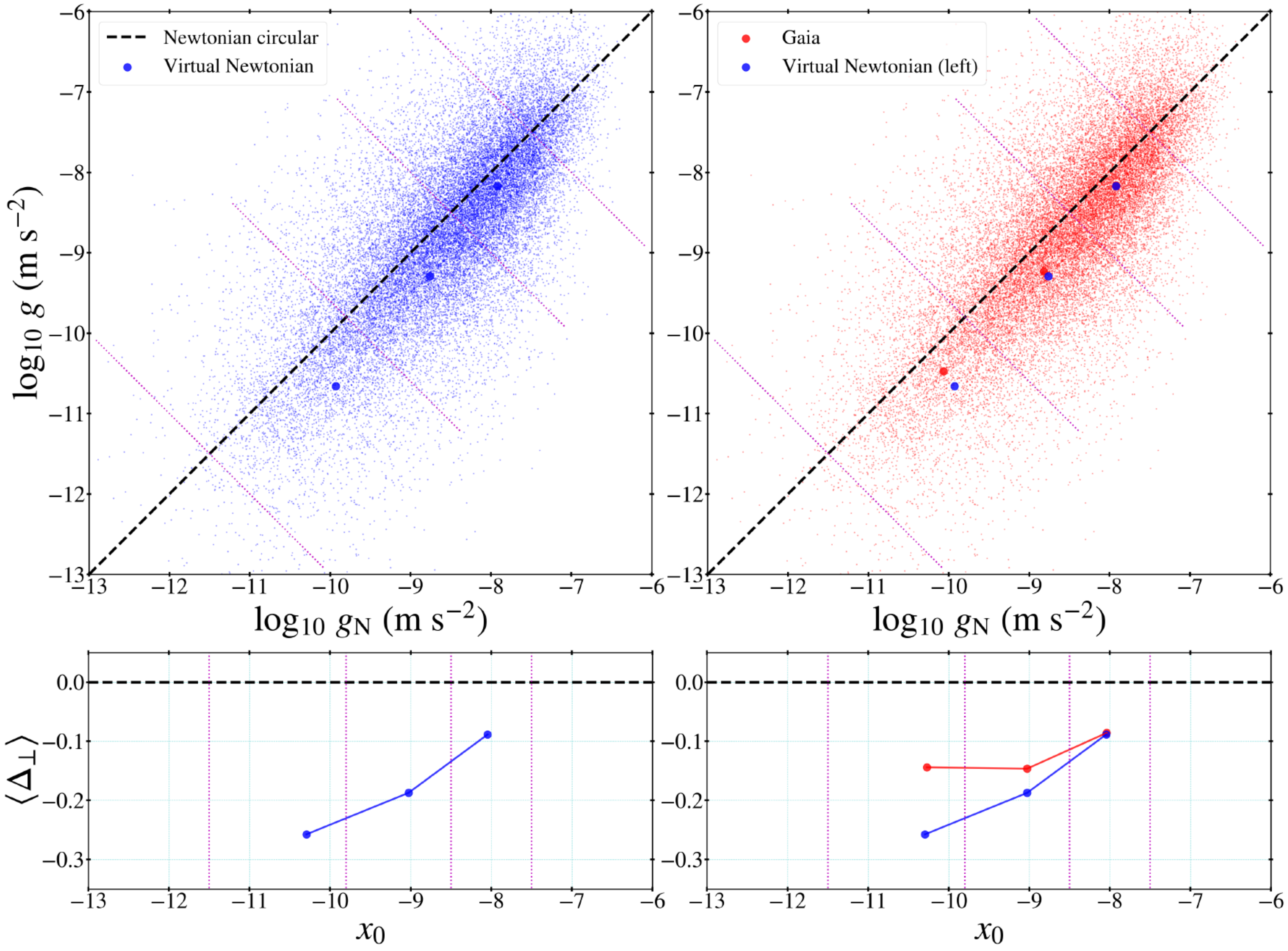
One deprojection result for the <80 pc sample



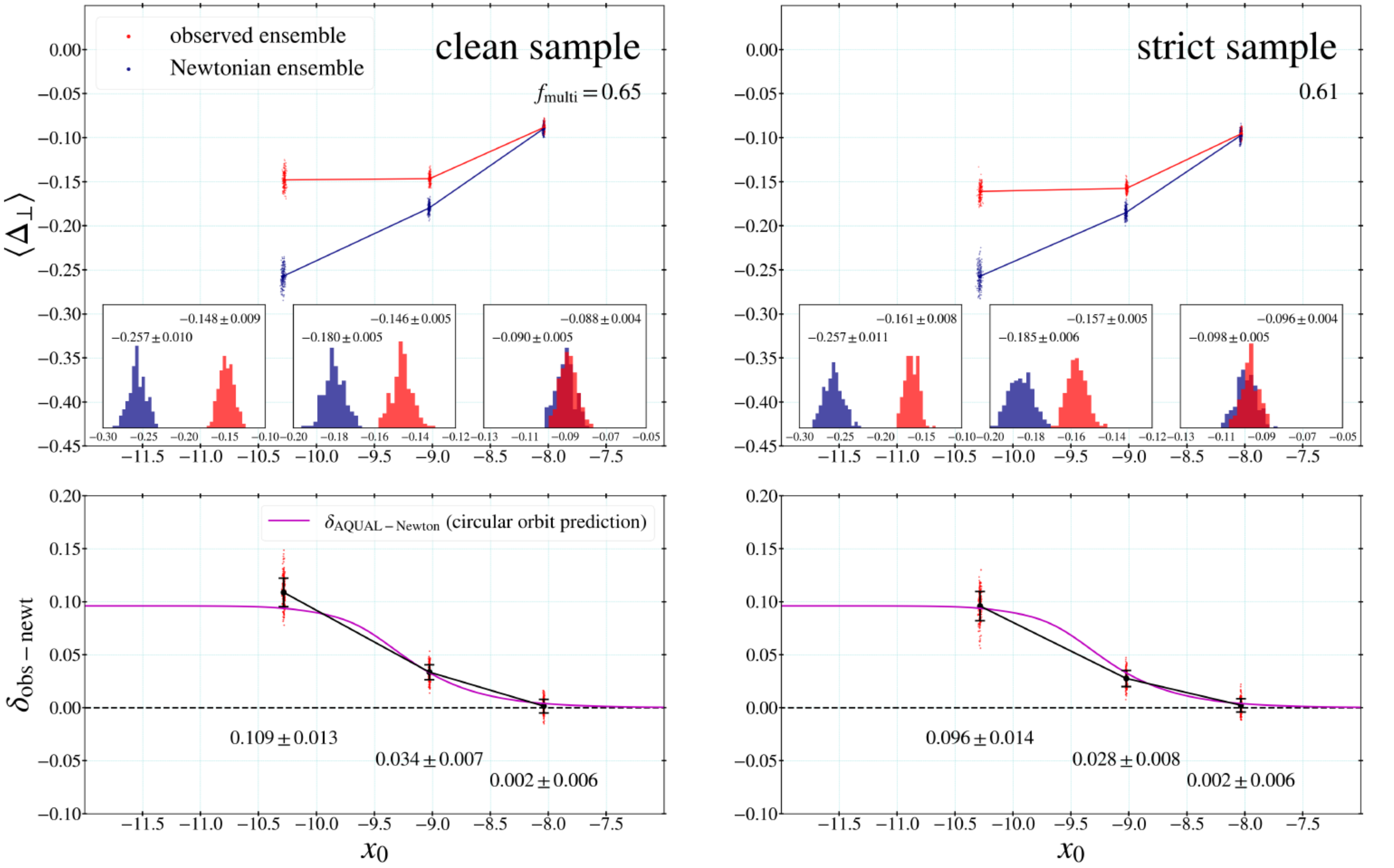
Distribution in 200 deprojections



Result for the <200 pc sample

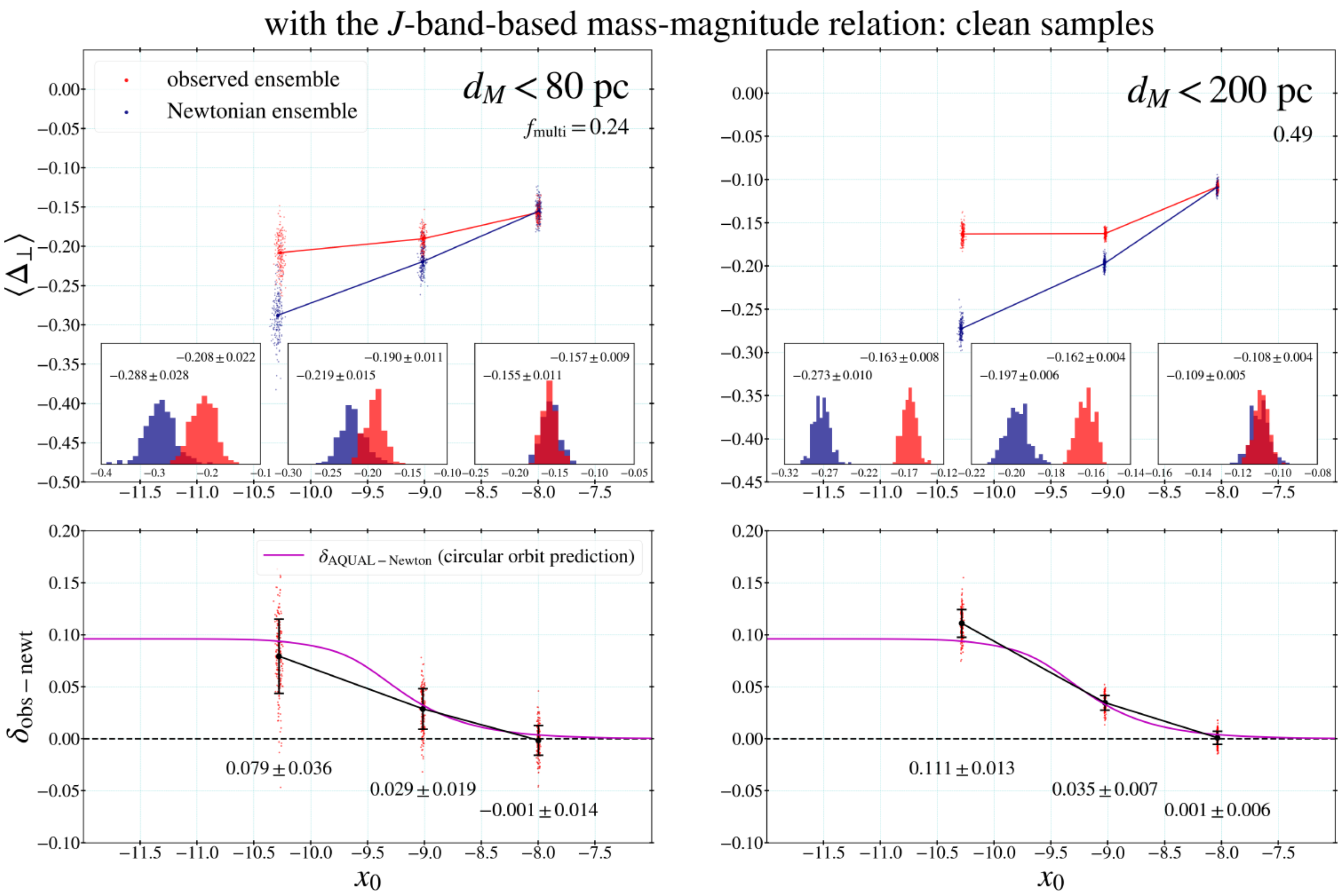


distance < 200 pc: $f_{\rm multi}$ fitted to the Newtonian prediction $\langle \delta_{\rm obs-newt} \rangle = 0$ at $x_0 = -8.0$

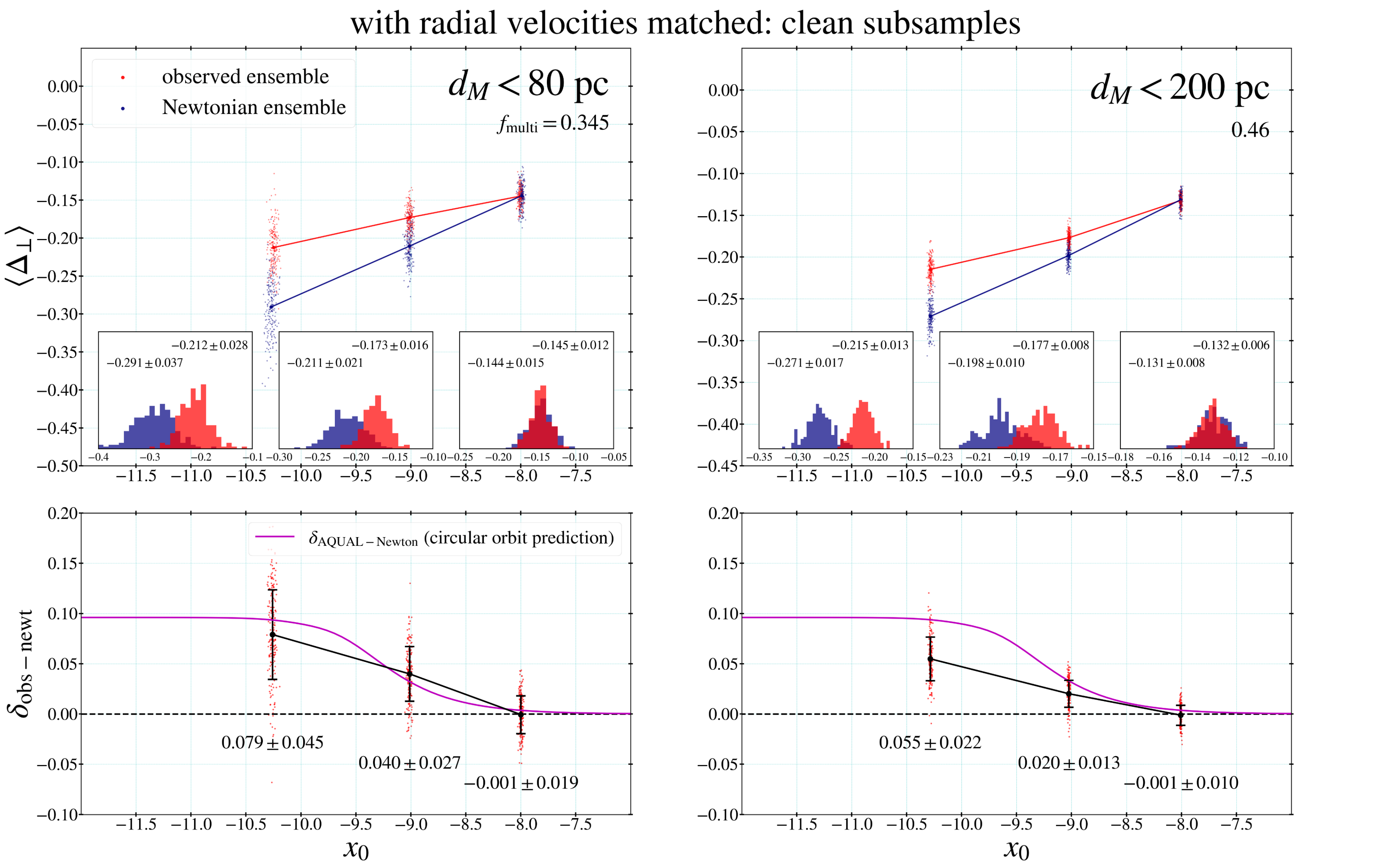


sample	$\delta_{\rm obs-newt}$ at $x_0 = -9.0$	$g_{\rm obs}/g_{\rm pred}$ at $x_0 = -9.0$	$\delta_{\rm obs-newt}$ at $x_0 = -10.3$	$g_{\rm obs}/g_{\rm pred}$ at $x_0 = -10.3$
$<$ 80 pc, clean	0.030 ± 0.019	$1.10^{+0.07}_{-0.07}$	0.088 ± 0.034	$1.33^{+0.16}_{-0.14}$
$<$ 80 pc, strict	0.028 ± 0.023	$1.10^{+0.09}_{-0.08}$	0.092 ± 0.036	$1.35^{+0.17}_{-0.15}$
$<$ 200 pc, clean	0.034 ± 0.007	$1.12^{+0.03}_{-0.03}$	0.109 ± 0.013	$1.43^{+0.06}_{-0.06}$
$<$ 200 pc, strict	0.028 ± 0.008	$1.10^{+0.03}_{-0.03}$	0.096 ± 0.014	$1.37^{+0.06}_{-0.06}$

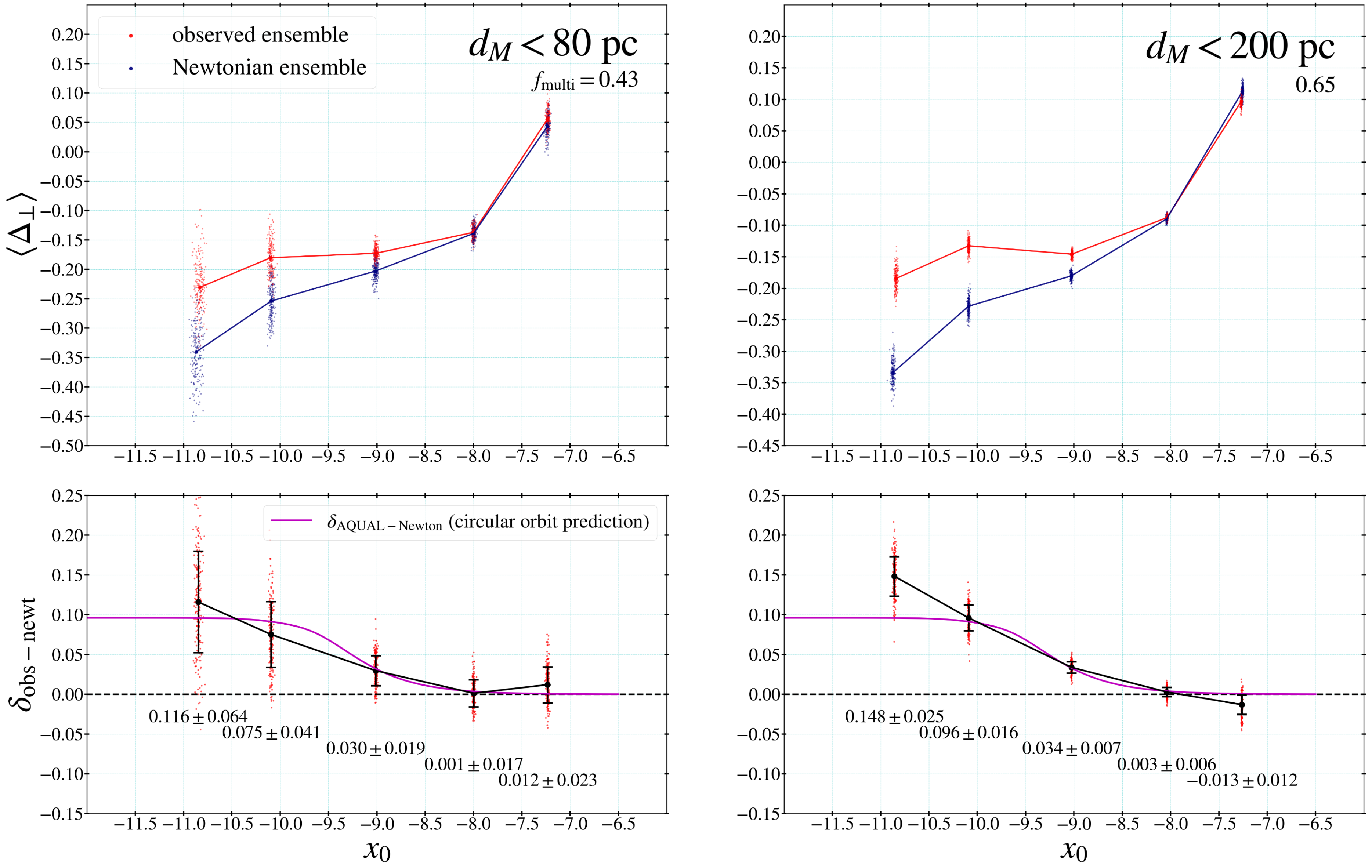
Results with the J-band based mass-magnitude relation



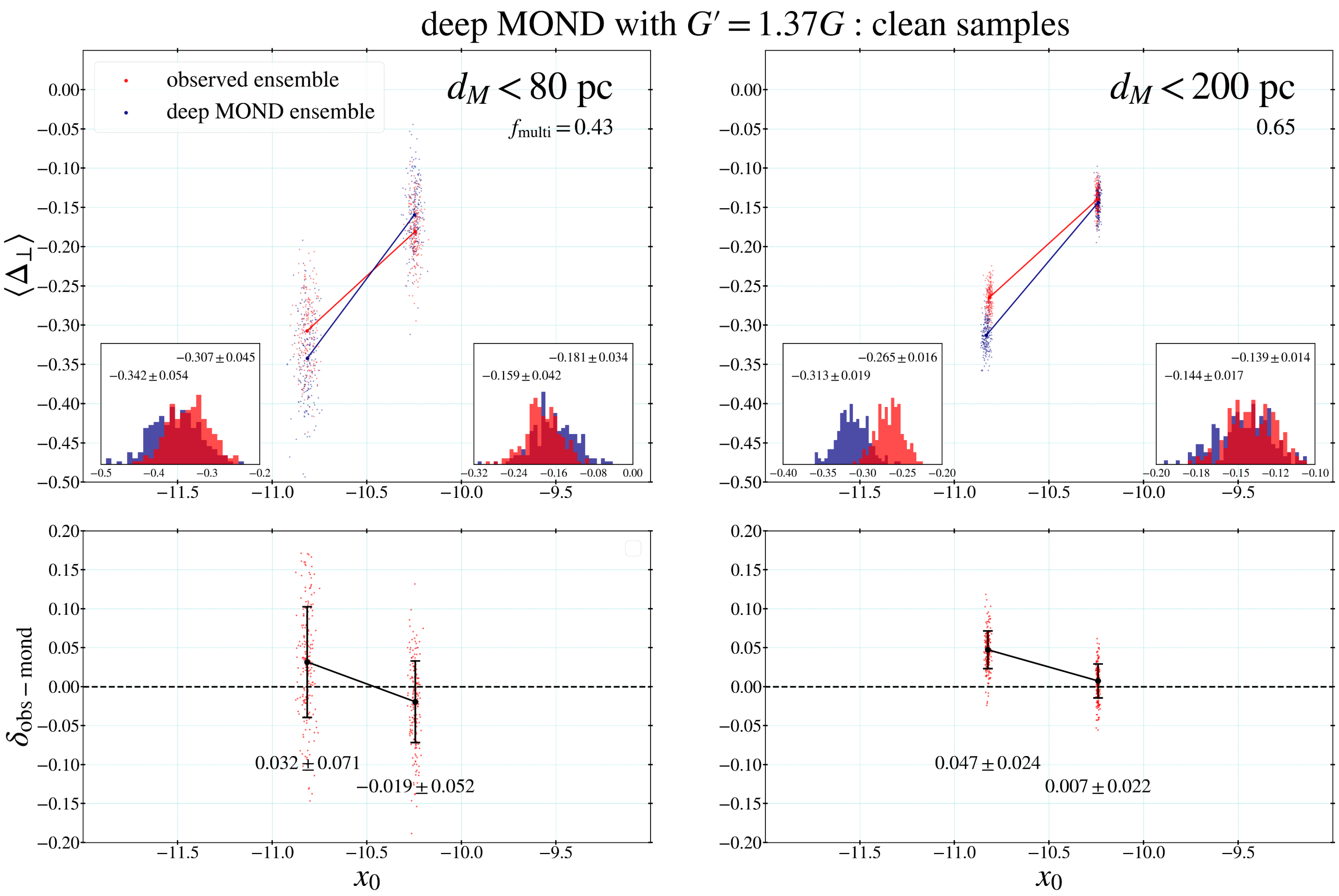
Subsamples with radial velocities matched



5 bins with the standard input: clean samples



Comparison with pseudo-Newtonian predictions



Conclusions

- Modified gravity by Bekenstein & Milgrom predicts both the inner and outer parts of galactic rotation curves correctly and naturally.
- Wide binary dynamics shows an immovable gravitational anomaly.
- Modified gravity by Bekenstein & Milgrom predicts corectly the gravitational anomaly in wide binaries.

Future prospects

- A new database of rotation curves (larger by a factor of 6 than the SPARC) will significantly improve the EFE test in galaxies.
- Later releases of Gaia may not only solidify the gravitational anomaly but also distinguish between modified gravity theories.